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A technology analysis to support acquisition of UAVs for Gulf Coalition Forces operations

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MONTEREY, CALIFORNIA

THESIS

A TECHNOLOGY ANALYSIS TO SUPPORT ACQUISITION OF UAVs FOR GULF COALITION FORCES OPERATIONS

by

Mohamed A. Alobaidli

June 2017

Thesis Advisor: Alejandro S. Hernandez
Second Reader: Matthew G. Boensel

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Reissued 27 Sep 2018 to reflect correct spelling of "Yemeni" throughout.

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A TECHNOLOGY ANALYSIS TO SUPPORT ACQUISITION OF UAVs FOR GULF COALITION FORCES OPERATIONS

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This thesis examines the potential effect of unmanned aerial vehicles (UAV) in the Decisive Storm operations. This analysis of UAV technology will assist Gulf Coalition Forces decision makers in their selection of the most suitable and cost-effective unmanned aerial vehicles to support detection operations. We use Map Aware Non-Uniform Automata, an agent-based simulation software platform, for the computational experiments. It models the operational area, system entities for the Gulf Coalition Forces, and the Houthi militia's attempts to cross the Saudi-Yemeni border. The software collects relevant data that can be translated into measures of mission effectiveness. Results from 10,400 simulation runs of Houthi efforts to infiltrate the operational area are analyzed using descriptive statistics, linear regression, and partition trees. These results, which include a significantly increased percentage of infiltrators being detected by Gulf Coalition Forces and improved time to detect them, support the use of UAVs in detection missions. Computer experimentations and analyses reveal the most significant capabilities the UAV should have to achieve operational goals. These significant capabilities fall within the U.S. Department of Defense's Group 3 UAV classification. Therefore, the Gulf Coalition Forces should consider procuring UAVs in that category to enhance detection in the operational area.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHP	Analytic Hierarchy Process
AOR	area of responsibility
AQAP	Al-Qaeda in the Arabian Peninsula
CI	confidence interval
C4I	command, control, communications, computers, and intelligence
DOD	Department of Defense
DOE	design of experiments
DP	design point
GCC	Gulf Corporation Council
GCF	Gulf Coalition Forces
GUI	graphical user interface
ISIS	Islamic States Iraq and Syria
ISR	intelligence, surveillance, and reconnaissance
LOS	line of sight
MANA	Map Aware, Non-uniform, Automata
MOE	measures of effectiveness
NOLH	nearly orthogonal Latin hypercube
NPS	Naval Postgraduate School
PSF	Peninsula Shield Forces
RSTA	Surveillance and Target Acquisition
SEED	Simulation Experiments and Efficient Designs
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle
UN	United Nations
U.S.	United States

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EXECUTIVE SUMMARY

Saudi Arabia leads the Gulf Coalition Force (Bahrain, United Arab Emirates, Qatar, and Kuwait) in executing Operation Decisive Storm, a military operation in Yemen against Houthi militias and their allies (Adaki 2015; Mello and Knights 2016). This operation defends the Yemeni government and protects the borders of northern Yemen's and the Kingdom of Saudi Arabia (*Al Jazeera* 2016).

Detecting the militia's scouts, infiltrators, and terrorists before they perform their reconnaissance or attack is critical for defending the border and Gulf Coalition personnel. David Roberts (2012) notes that during the Gulf Coalition Force (GCF) operation in Yemen, the Houthi militias successfully gathered location information about the Emirati and Bahraini troops. With this information, the Houthi militias were able to fire a Soviet Tochka missile that killed more than 50 soldiers. Other attacks have also resulted in losses to the GCF, frequently because of the force's inability to detect those infiltrators.

This research examines the potential effects of employing unmanned aerial vehicles (UAV) in the Decisive Storm Operations in Yemen. Results will assist decision makers in their acquisition selection of an appropriate UAV to support detection operations. Furthermore, this study shows how the GCF participating in Yemeni operations can improve border security and defend their operational areas against enemy incursions and reconnaissance. This thesis analyzes the use of the UAVs in conjunction with detection methods already being employed by ground forces for the GCF's Decisive Storm operational area. Using the UAVs in the Decisive Storm operational area might increase the probability of detection of those infiltrators and militia members.

This thesis uses Map Aware Non-Uniform Automata (MANA), an agent-based simulation software platform. First, we examine the effect of introducing UAV technology into the detection operations. Applying computer experimentation to model the Houthi militia's attempts to cross the border provides insights into the Gulf Coalition Forces' intelligence, surveillance, and reconnaissance (ISR) capabilities. Additional experimental designs effectively explore the required UAV characteristics that can enhance the detection mission. Regression analysis and partition tree analysis provide

additional assistance in examining all design point options. Finally, a relative cost and benefit analysis helps in identifying the design option we wish to pursue.

The introduction of unmanned aerial vehicles supporting the detection missions in the Decisive Storm operation reveals significant improvements in the percentage of infiltrators that the Gulf Coalitions Forces detect as well as in the time it takes to detect them. Nevertheless, in the first introduction, the UAVs lacked the necessary capabilities and thus were unable to support GCF detection operations. Therefore, we analyzed more computer experimentation to discover the UAV characteristics necessary to satisfy the GCF operational goals. Using regression analysis we sought to uncover the most significant factors having an impact on the UAV's detection capabilities; this analysis indicated six such factors. Furthermore, the partition tree analysis identified 25 design point options, among 260 examined, that met the operational goals when the stealth level of the enemy is low. By contrast, we found only seven design point options meet the operational goals when the enemy stealth level is high.

Finally, we calculated a relative cost estimate for the total system price for all 260 design point options. The most desirable option is revealed in the relative cost efficiency analysis.

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I dedicate this thesis to our troops participating in the Decisive Storm operation in Yemen and especially to our heroes who passed away during the operations.

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I. INTRODUCTION

A. PURPOSE

This research examines the potential effect of employing Unmanned Aerial Vehicles (UAV) in a detection operation in the Decisive Storm operation in Yemen. Results will assist decision makers in their acquisition selection of an appropriate UAV to support detection operations. Furthermore, this study can show how the Gulf Coalition Forces (GCF) participating in the Decisive Storm operations can improve border security and defend their operational areas against enemy incursions and reconnaissance.

B. MOTIVATION

Saudi Arabia leads the Gulf Coalition Force (Bahrain, United Arab Emirates, Qatar, and Kuwait) in executing Operation Decisive Storm, a military operation in Yemen against Houthi militias and their allies (Adaki 2015; Mello and Knights 2016). This operation defends the Yemeni government and protects northern Yemen's and the Kingdom of Saudi Arabia's borders (*Al Jazeera* 2016).

Detecting the militia's scouts, infiltrators, and terrorists before they perform their reconnaissance or attack is critical for defending the border and the Gulf Coalition personnel. Roberts (2012) stated that during the GCF operation in Yemen, the Houthi militias successfully gathered location information about the Emirati and Bahraini troops. With this information, the Houthi militias were able to fire a Soviet Tochka missile that killed more than 50 soldiers. Other occasions have also resulted in losses to the GCF, frequently because of the force's inability to detect those infiltrators.

This chapter provides information about the Gulf Corporation Council (GCC) and its integrated military forces, the Peninsula Shield Forces (PSF), for which the Unmanned Aerial System (UAS) is a potential solution. A short background about the conflict environment and the threats confronting the Kingdom of Saudi Arabia's border and on all other GCC members follows this discussion. This chapter lists major challenges in securing the Yemeni-Saudi border, describes the inadequate detection means used by the GCF in that region, and suggests probable solutions.

C. BACKGROUND

This section provides essential information about the GCC and the conflict environment. It discusses the Decisive Storm objectives and challenges. This section further explains the current detection means used by the GCF and other possible options to enhance the detection operations.

1. GCC Strategic Location and Surrounding Challenges

The six GCC countries (Kingdom of Saudi Arabia, Kingdom of Bahrain, United Arab Emirates, Oman, Kuwait, and Qatar) are located in the Arabian Peninsula. Together, these countries form a coalition for resolving or mitigating political, economic, and security issues. They have merged their security policies and defense capabilities to form the Peninsula Shield Forces (PSF). The GCC states share borders with Yemen in the southern part of the peninsula and Iraq and Jordan in the northern part (Figure 1).

Figure 1. The Gulf Corporation Council States. Adapted from Secretariat General of the GCC (2017).

The GCC countries are surrounded by countries that have internal conflicts and elements of destabilization making it critical for the GCC states to protect their borders against terrorists, spies, members of criminal organizations, and illegal immigrants.

Investing in detection and intelligence equipment is essential to maximize border protection. In particular, rapid technological changes and evolving concealment techniques used by terrorists demand new means for detection and intelligence gathering.

2. Decisive Storm Objectives

In March 2015, Saudi Arabia formed the Gulf Coalition to defeat the Houthi militias and those loyal to the former president of Yemen and to restore legitimacy of the Yemeni government. This quest was based on United Nations (UN) Resolution number 2216 (UN Security Council 2015).

Along with Gulf States (except Oman), other nations have joined the military operations (Figure 2). The United States has joined the operation and provides logistical and intelligence support to the GCF during the military operation in Yemen (Alshabeeb 2015). Graham (2016) reports that United States' (U.S.) forces as well as the United Kingdom C4I (command, control, communications, computers, and intelligence) personnel have been deployed in the operation centers in command and control to provide assistance in controlling air strikes and detecting threats.

Figure 2. Decisive Storm Military Coalition Forces.
Source: Alshabeeb (2015).

3. Conflict Environment

After the Iraq war in 2003 and the Arab Spring, Iraq and Yemen suffered from an unstable security environment, as well as a weak economy (Cordesman, 2015). Both countries have borders adjacent to GCC nations. Weak security situations and availability of arms and weapons have nurtured a fertile environment for terrorist organizations to start their operations. Terrorist organizations increase the threat of smuggling and drug trafficking as well as migrating terrorist members into the GCC countries to vandalize civilian- and government-owned properties. Michael Knights (2006) has pointed to this issue, stating that "contiguous borders with Yemen and Iraq—both key theaters of operation for jihadists—make Saudi Arabia a critical transshipment point for weaponry and jihadists engaged in multidirectional flow of personnel and equipment throughout the GCC" (35). He argues that the threat posed by terrorists from Yemen and Iraq necessitates enhancing security for GCC countries that share borders with Yemen and Iraq.

4. Decisive Storm Challenges

Detecting infiltrators is the key to success for the GCF if they want to ensure border security. Additionally, securing the operational area against enemy incursion and reconnaissance is critical. There are many challenges that limit the detection process in that region.

a. Technological Challenge

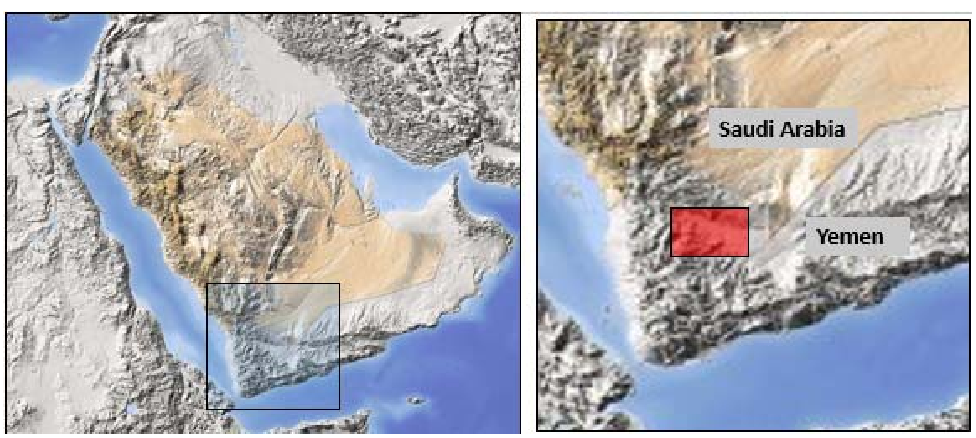
The first challenge is detecting the militia's scouts or other infiltrators, which is critical for securing the border and protecting the Coalition Forces. Electronic detection equipment such as ground radars is inadequate because of the size of the operational area and the characteristics of the terrain that interfere with such equipment. This leaves the GCF vulnerable to the Houthi militias, who have been sending their scouts across the border to collect reconnaissance information about the Coalition troops' locations to attack and cause damage.

b. Terrorism Challenge

The GCF must contend with terrorist organizations, such as Al-Qaeda in the Arabian Peninsula (AQAP) or the Islamic State in Iraq and Syria (ISIS or Daesh) located in Yemen that are trying to enter the Arabian Peninsula to cause havoc. Saeed Al-Batati and Kareem Fahim (2015) report that terrorist organizations located in Yemen, such as AQAP and ISIS, are trying to take advantage of the instability and loss of border control to enter the Arabian Peninsula and carry out their missions. Al-Batati (2016) further explains that after the Yemeni troops loyal to the former president left the city of Mukkala in Yemen, they created an opportunity for terrorists. Thus, he notes, Al-Qaeda members promptly took over the city knowing that the GCC forces and the Coalition Forces were otherwise occupied in conflict with the Houthi militias.

c. Terrain Challenge

Another challenge for the GCF in the operation in Yemen is the geography. The area of operation, illustrated in Figure 3, is located in the southwest part of the Arabian Peninsula where hills and rugged mountains dominate. Gulf Coalition Forces are accustomed to working in the eastern part of the Arabian Peninsula where dry desert and coastlands cover most of the area where detection of infiltrators is easier (Hesham 2007; Witty 2001; Fryberger et al. 1984).



The image on the right shows an enlarged image of the Yemeni-Saudi border and the operation area is shaded in red

Figure 3. The Arabian Peninsula Landscape. Adapted from Nielsen (2012).

5. Detection and Intelligence Methods Used in Decisive Storm Operations Are Inadequate

Manned aircraft patrol the border area in this military operation. They also provide intelligence, surveillance, and reconnaissance (ISR) over the border or around the operational areas where troops are located. The Gulf Coalition ground forces utilize a variety of methods and equipment to detect (1) terrorists trying to cross the border at Saudi Arabia and (2) Houthi militias gathering information undercover to attack GCF troops. Electronic radar sensors, night vision scopes, ground motion sensors, and detection monitors have proven ineffective to detect these infiltrators. While some manned aircraft support has proven successful, the cost associated with this method is prohibitive. The major reason for the failure of other methods is the rough topography of the operational area.

Rough topography, the size and shape of the operational area are significant factors that limit the effectiveness of the GCF to prevent intrusions. These challenges motivate the employment of new detection technologies to bolster GCF capabilities.

The author visualized the process by which the GCF would decide on what detection options are better suited for the force. Following the systems engineering mindset in defining the problem and suggesting a possible solution, the author used a multiple-criteria weighted scoring model with author derived weights and scores to examine the best detection method for the GCF for use in the operation area.

Options were evaluated against each other and given a weighting based on their importance. Total rank score determined the most effective option to be employed by the GCF. Table 1 shows the four options evaluated; the UAV, with the highest score of 15.55, is the best choice for GCF purposes. Based on this preliminary study and the GCF's needs, the UAV is the focus area in this thesis; further detailed analysis of UAV characteristics and cost-related concerns are presented in subsequent chapters.

Table 1. Analysis of Detection Options for the Gulf Coalition Forces.

Evaluation Measures		Alternatives Score				Alternatives Weighted Score			
(Architectural Drivers)	Weights	**Manned aircraft**	**Balloons**	**Ground forces**	**UAV**	Manned aircraft	Balloons	Gound Forces	UAV
Cost	0.8	1	2	3	4	0.8	1.6	2.4	3.2
Detection Range	0.7	4	2	1	3	2.8	1.4	0.7	2.1
Tough terrain employment	0.6	3	1	2	4	1.8	0.6	1.2	2.4
Ground forces integration	0.7	1	3	4	2	0.7	2.1	2.8	1.4
Mobility	0.5	2	1	4	3	1	0.5	2	1.5
Susceptibility	0.65	4	1	2	3	2.6	0.65	1.3	1.95
Operational duration	0.75	2	3	1	4	1.5	2.25	0.75	3
					Total Weighted Score ->	11.2	9.1	11.15	15.55
					Overall Rank ->	2	4	3	1

The motivation to employ UAV technology in the operation in Yemen is bolstered by anticipated success in enhancing the detection and ISR mission against terrorists and infiltrators, as well as by considering other factors such as the cost and limitations associated with other detection options.

D. PROBLEM STATEMENT

There is inadequate analysis to support acquisition decisions to procure UAV technology that can significantly improve Gulf Coalition Force capabilities to detect crossings or encroachments on the border.

E. SCOPE OF THE RESEARCH

This study can aid GCF decision makers in their acquisition decision for a suitable UAV to support detection missions. Furthermore, this study can show the importance of integrating the air surveillance UAV with ground forces and even the efficacy of replacing other detection techniques currently used. The study also identifies the UAV technology employment options to serve the region.

This thesis analyzes the use of UAVs along with other detection methods already used by ground forces for the GCF. Using the UAVs in the Decisive Storm operational area might increase the probability of detection of those infiltrators and militia members.

F. RESEARCH QUESTIONS

This study addresses the following major research question: How can a UAV technology assessment inform the Gulf Coalition Force's acquisition decisions for improving its early warning detection capabilities in the Decisive Storm operation?

Specifically, this research is guided by these questions:

- To what degree can UAV technology improve the detection capability for the GCF to increase border security and better defend the Saudi-Yemen border?
- What UAV characteristics are most important for the GCF to consider in procuring UAV technology?
- What combination of UAV capabilities most effectively increases target detection and classification in the operational area?
- What number of UAV systems is required to achieve a certain threshold for detection and enhance border security?
- How will cost constraints influence the selection and eventual purchase of the ideal UAV?

G. THESIS ORGANIZATION

The remainder of this thesis is organized as follows: Chapter II reviews other related research that identifies a similar UAV role in detection as well as agent-based modeling studies. Chapter III explains the setup of the model and the scenarios chosen for the purpose of this thesis. This discussion includes brief details about agents and their settings as well as explanations of the terrain map and elevation maps used in this analysis. Additionally, Chapter III explains the design factors chosen for this analysis and method to explore the design of experiment space. Chapter IV analyzes the experiment results and reveals the best UAV characteristic options for the GCF. Chapter V concludes the thesis by answering the research questions to illustrate their achievability.

II. LITERATURE REVIEW

This chapter provides background information on UAVs and their benefits in modern warfare. Next, it discusses past studies about the UAV role in border control and studies about modeling UAVs to design a system. Furthermore, it includes an explanation and discussion of the modeling and simulation techniques that influence the approach used in this thesis.

A. UAV BACKGROUND

The U.S. government is the main defense supplier for the allied Arabian Gulf countries (Serrano and Vats 2016). However, due to the restrictions on the sale of armed and unarmed UAVs that the United States Department of Defense has imposed on the Gulf States (Cordesman and Peacock 2015), the Gulf States lack extensive experience with this technology.

A brief summary of the unmanned aerial vehicle technology will assist in the acquisition decision maker's understanding of the UAV system. UAVs are a component of the unmanned aircraft system according to the U.S. Department of Defense (DOD) "UAS Road Map for the UAS from 2005 to 2030" (Cambone et al. 2005). DOD refers to the UAS as the whole system whose elements are used to control the unmanned aircraft. Examples are the vehicle, human operator, payload and other elements. This thesis limits its focus to the component of the UAS system highlighted in Figure 4.

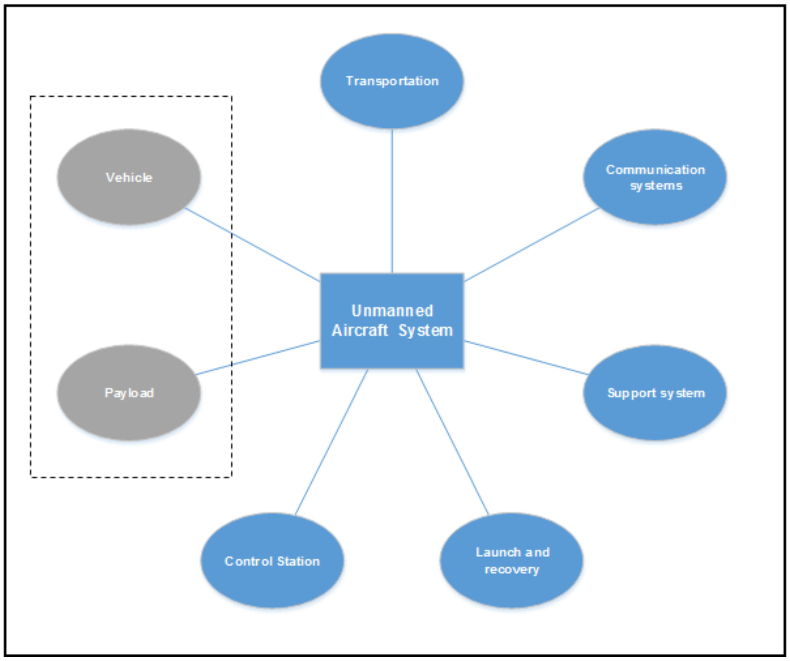


Figure 4. Unmanned Aircraft System Components.

UASs come in different categories for a variety of mission types. Charles Sulewski (2005) describes four different classification of UASs in support of the U.S. Army: Class 1 provides Reconnaissance, Surveillance and Target Acquisition (RSTA) capabilities for the platoon level; Class 2 provides the same capability as Class 1 in addition to target designation for the platoon and company level; and Class 3 improves upon Class 2 systems by adding a communication relay facility on the UAS for the combined arms battalion level. Finally, Class 4 UASs have the capability of flying in conjunction with manned aircraft during missions. Table 2 shows the latest UAS classifications based on DOD information.

Table 2. Current UAS Systems Classified by U.S. Army. Source: United States Army (2010).

Category	Size	Take-off weight	Altitude	Airspeed
Group 1	Small	0–20	<1200	<100
Group 2	Medium	21–55	<3500	<250
Group 3	Large	<1320	<18000	<250
Group 4	Larger	>1320	<18000	Any airspeed
Group 5	Largest	>1320	>18000	Any airspeed

The UAV's rapid technological evolution has changed its role in modern warfare. It is an important part of combat due to the additional advantage it adds to the forces.

B. RESEARCH STUDIES

Many research studies address the benefit of UAV for homeland security and show the major role of the UAV technology in this matter. Additionally, significant number of thesis research conducted by Naval Postgraduate School (NPS) students about modeling UAVs to design a system, depict the importance of UAV in today's warfare.

1. UAV Effectiveness in Border Security

Unmanned aerial vehicles have become a key player in today's warfare due to the advancement in technology. UAVs can cover a wide range of tasks depending on the requirement of the user. UAVs have associated cost and finances that stakeholders must consider relative to other procurement requirements. However, many benefits outweigh those costs when it comes to the security of borders against terrorists.

Christopher Bolkom (2004) points to the UAV costs and benefits. He states that the UAV could address shortcomings in border security surveillance if the correct sensor is used; that is, a sensor capable of identifying targets precisely. Similarly, UAVs capable of longer flight times can influence border security as they can sustain coverage for longer periods. He also points out the higher cost associated with the purchase of the UAV in comparison with manned aircraft, that difference in cost is offset by the UAV's superior endurance. Bolkom also identifies some drawbacks associated with UAVs, such as the high rate of accidents, and relatively lower redundancy and survivability factors in UAV design compared to manned aircrafts.

Chad Haddal and Jeremiah Gertler (2010) list the strengths and weaknesses of deploying UAVs along the United States border. They assert that UAVs could fill the detection gap associated with currently used surveillance equipment. In addition, UAVs can act as range extenders for border surveillance when comparing UAVs with traditional border surveillance techniques. Nevertheless, UAVs have some weaknesses, according to

Haddal and Gertler, associated with cost of operation, such as their high accident rate and the degradation in target detection under bad weather conditions.

2. Modeling UAVs in Battlefields

Begum Ozcan (2013) has analyzed the use and effectiveness of UAVs to support the security of Turkey’s east border, adjacent to the Iraqi border, where terrorist members locate and travel between the two countries. In her study, she illustrates the difficulties in detecting terrorist members located in tough, mountainous terrain using regular detection equipment and manned aircraft. The UAV can be adjusted technologically to meet the stakeholders’ requirement for such a need, if the affecting factors can be determined. Ozcan built a model to explore the best technological capabilities of a UAV that can be used to expand coverage along the Turkey-Iraqi border. She examined possible effects that UAVs could have in detecting and classifying infiltrators and terrorist members along the border. Her study showed that the use of a UAV is very effective in the detection and classification of terrorist activity in this challenging region, taking into account the significant technical factors that affect UAV detection and classification performance.

Another study conducted by Bahri Yildiz (2009) focuses on the importance of border protection in deterring terrorist members, human and drug trafficking, and illegal migration by improving the detection methods along the border. In his study, Tucson, Arizona, was modeled using Map Aware Non-Uniform Automata (MANA) software to investigate the added value of UAVs in border security along with other detection assets, such as ground force agents, security surveillance towers, sensors, predator UAVs, and communication centers. Yildiz concludes that UAVs could provide an additional benefit in capturing illegal infiltrators and could increase the security of the borders. According to the outcomes of his model, three affecting factors to improve the detection means are manpower of the patrolling agents, communication network infrastructures, as well as the UAV itself.

Fatih Sen (2015) points to the challenges that Turkey faces protecting and securing the Turkey-Iraqi border and the limitation to the manned aircraft used for the

security of border missions. The limited fuel capacity of manned aircraft and geographical limitations across the border have encouraged the Turkish government to explore other means of detection to enhance their ability to counter terrorists in that region. Sen (2015) also uses the MANA software to model different scenarios that are possible in that region and analyzes the outcomes to test the use of UAVs and manned aircraft. His study outcome shows that with the use of UAVs, additional target identification could be observed, which can lead to protecting the borders more effectively against terrorist attacks.

C. AGENT-BASED MODELING SIMULATION

Simulation software plays a major role in the analysis of combat and supporting decision making, as it shapes solutions to the problem and explores numerous possible outcomes with low cost. Several such applications include wargaming, training, system overall efficiency simulators, and modeling software enables different military tactics to be practiced. Thomas Lucas et al. (2012) note that DOD decision makers usually use simulation to make decisions on acquisition programs, equipment employment choices, and possible tactics and procedures.

Eric Bonabeau (2002) lists several advantages of agent-based simulation over other techniques. Such advantages include the ability to

- capture emergent events that result from interactions of individual entities,
- provide natural description of the system or closer to reality simulation,
- provide flexibility of the system by adding or subtracting agents or objects.

Simon Taylor (2014) asserts that "agent based modeling has evolved as a natural response to the need for complex system modeling" (3). He also mentions that agent-based modeling has the capability to represent a system in a sensible way, more so than other traditional techniques. Based on his definition of the agent-based model, each agent-based model should have four characteristics:

- Each agent should have a set of attributes that define the condition of the agent and his actions.

- Relationships must define how the agents relate and interact with other agents and the environment in the model.
- The environment where the agent lives and variables define how he deals with the environments.
- A system consists of agents, environment, and the relationship between them.

The agent-based modeling is generated using a suitable programing tool and can be executed through a wide range of commercially available programs, such as MANA, MATLAB, C++, and other programs.

D. MAP AWARE NON-UNIFORM AUTOMATA SOFTWARE

Map Aware Non-Uniform Automata, or MANA, is one of the simulation programs that incorporates agent-based modeling. MANA simulation captures the unexpected outcomes of interactions between agents based on their behavior in the simulation environment. Agents could be in form of a human, airplane, UAV, vehicle, ship, and other types of key players in the simulations. As mentioned earlier, MANA is an agent-based distillation model that excludes unneeded complex computations, but at the same time produces all necessary data required for the analysis. MANA was developed to explore key concepts: (1) situational awareness, (2) communications, (3) terrain maps, (4) waypoints, and (5) agent personality change due to events (McIntosh 2007).

Ozcan (2013) identifies some of the advantages of MANA. It is easy to learn in a short time compared with other modeling software, is user friendly, and has a simple graphical user interface (GUI) that enables building scenarios in a shorter period. Many other Naval Postgraduate School theses have used MANA to analyze UAV capabilities and effectiveness such as those by Arif Ipekci (2002), Sulewski (2005), Ozcan (2013), Sen (2015), and Whye Kin Melvin Cheang (2016).

III. METHODOLOGY

A. INTRODUCTION

To address the research questions in this study, we use a modeling and simulation based systems engineering approach. We use abstractions of the relevant entities in the operational scenario to conduct simulation experiments that produce data with the appropriate pedigree that enables in-depth analysis and examination to support acquisition decisions. This chapter starts with a discussion of the measures of effectiveness (MOE), followed by a scenario description for the situation in which the system will be placed and simulated in the MANA software. Following that is a discussion of significant factors that might influence the MOE. Finally, we describe the design of experiments that we use to efficiently and effectively explore the decision space.

B. MEASURE OF EFFECTIVENESS

John M. Green (2001) states that every system development process should have a performance analysis; it is essential to evaluate the system's development within its resources. Part of this performance analysis is the performance measurements that need to be carefully selected, also called the MOE. Green defines the MOEs as "the measure of effectiveness that provide a quantifiable benchmark against which the system concepts and implementation can be compared" (1).

The measure of effectiveness should be allied with defining and achieving the operational concerns. This thesis embraces two MOEs that are related to the improved effectiveness of the GCF's detection capabilities when UAVs are integrated with ground radars. Those two MOEs will aid in answering the research questions of this study. Simulations have red and blue agents to describe different factions in the operational environment.

The first MOE is the percentage of the total red agents detected (MOE 1). This percentage is obtained at the end of each run. Each simulation run has 500 red agents trying to cross through the military restricted area. MOE 1 represents the added benefits

of employing a UAV in conjunction with the available ground radars. Detecting 100% of the red agents is the ultimate goal of the GCF commanders, but it is unrealistic. Therefore, we set the MOE 1 threshold to 90% of the red agents, which equates to 450 red agents.

The second MOE is the time it takes to detect 40% of the red agents (MOE 2). Detecting red agents at the early stages of the operation is important so that the GCF can determine the center of activity to pursue. The mountainous environment that the GCF must traverse to engage infiltrators makes timely detection a necessity to rally a timely response. As mentioned in earlier chapters, Houthi militias (red agents) are adept in rugged terrain and travel faster, which requires the GCF to respond quickly. The total simulation run time is 24 hours. We set the MOE 2 threshold to 3.55 hours or 15% of the total simulation time.

C. SCENARIO DESCRIPTION

The scenario in this model is based on the historical attacks by Houthi militias against the GCF that have resulted in the deaths of Saudi, Bahraini and Emirati troops. Houthis' reconnaissance missions are successful due to the weak detection equipment available to the GCF. Additionally, Houthis have the advantage of using the rugged terrain to conceal their movement when gathering information.

In the scenario, blue forces represent the GCF, who try to defend against the enemy and detect them before they reach their goals. The GCF have radars across the Saudi-Yemeni border to detect infiltrators before they cross the border and reach their objectives. However, ground radars have a low probability of detecting the enemy because of the terrain and the enemy's ability to avoid detection.

The red forces are the Houthi militias who try to make their way to the border to perform reconnaissance without being detected by blue force detection equipment. As previously noted, there are 500 red agents in this scenario.

We are examining the improvement in detecting infiltrators when UAVs are employed by the GCF. For this reason, we initially model a baseline configuration that

represents the current detection equipment used by the GCF. Later on, we add UAVs to examine improvement in detection. Data is collected at the end of each configuration run to develop an analysis to answer the thesis questions.

1. Baseline Configuration (Ground Radars Only—Current Capabilities)

The baseline model configuration simulates the current situation of the GCF method explained previously. Five hundred red agents divided into ten groups of 50 each, are trying to cross the border successfully without being detected in the military restricted area. The GCF ground radars are the only detection equipment used in this configuration. The baseline configuration results will be used for comparison and analysis against the improved configuration.

The appearance of any agent in the restricted area is considered a target with which GCF must deal. It is a restricted area and presence in this region is prohibited. Figure 7 depicts the battlefield locations. If a red agent is detected by any of the radars, it is reported to the GCF and eliminated from the scenario. Figure 5 shows the locations of the red agents, ground radars, and borderline in the baseline configuration.

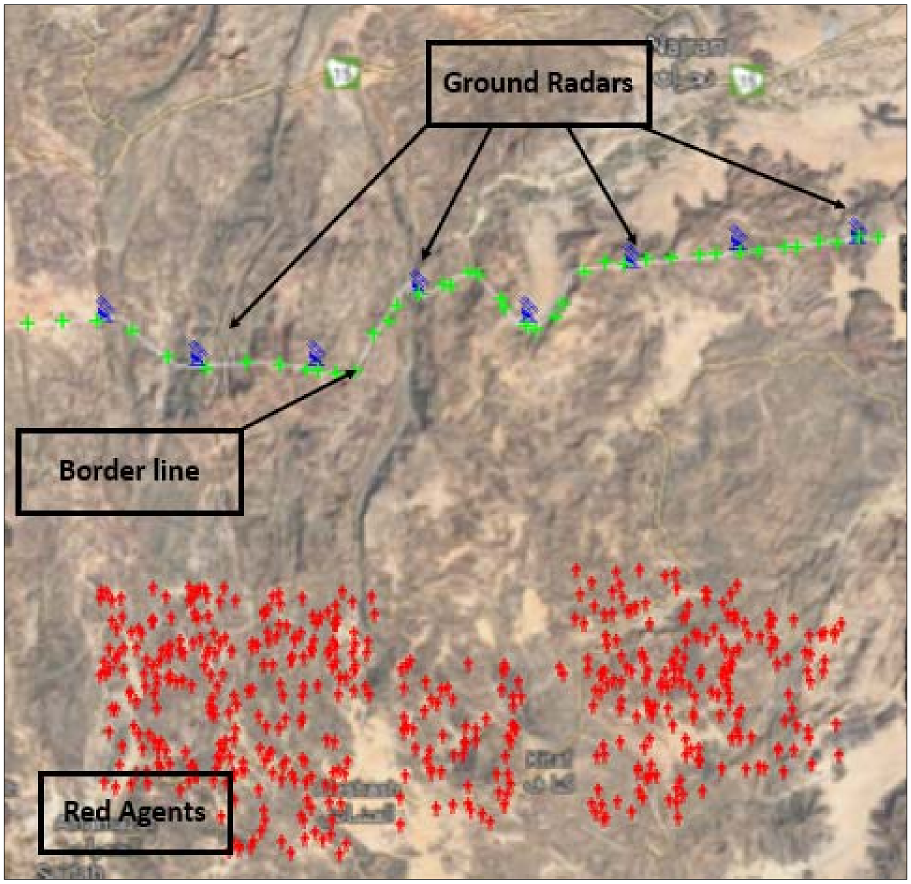


Figure 5. Baseline Configuration Agent Locations.

2. Establishing the Capabilities of the GCF Radars

Because the number of radars used across the border by the GCF, the probability of detection by the radars, and the radar locations are all classified, we implement a reverse engineering approach to build an initial model that reasonably represents the GCF detection capability with baseline radars.

Multiple combinations of the number of radars, radar ranges, and radar times between detection were tested in the model. These combinations resulted in a percent of red agents detected. To establish a baseline configuration, the author used the combination of value settings of the number of radars, radar ranges, and radar times between detections that resulted in approximately 30% of red agents being detected. This percentage is the author's best estimate based on his operational experience and an understanding of the GCF policies. More details are provided in Chapter IV.

3. Improved Configuration (Ground Radars and UAVs)

The improved configuration is similar to the baseline configuration except for the employment of the UAVs to increase the detection rate. UAVs will patrol the area of responsibility (AOR) or the restricted area to detect red agents. This configuration will employ different numbers of UAVs (from one to four). As the number of UAVs increases, their search pattern and the area of coverage change in that particular scenario. Results of the baseline configuration will be compared to the improved configuration to address the research questions. Figure 6 shows a screenshot of the improved configuration with four UAVs; the UAVs are circled in the figure.

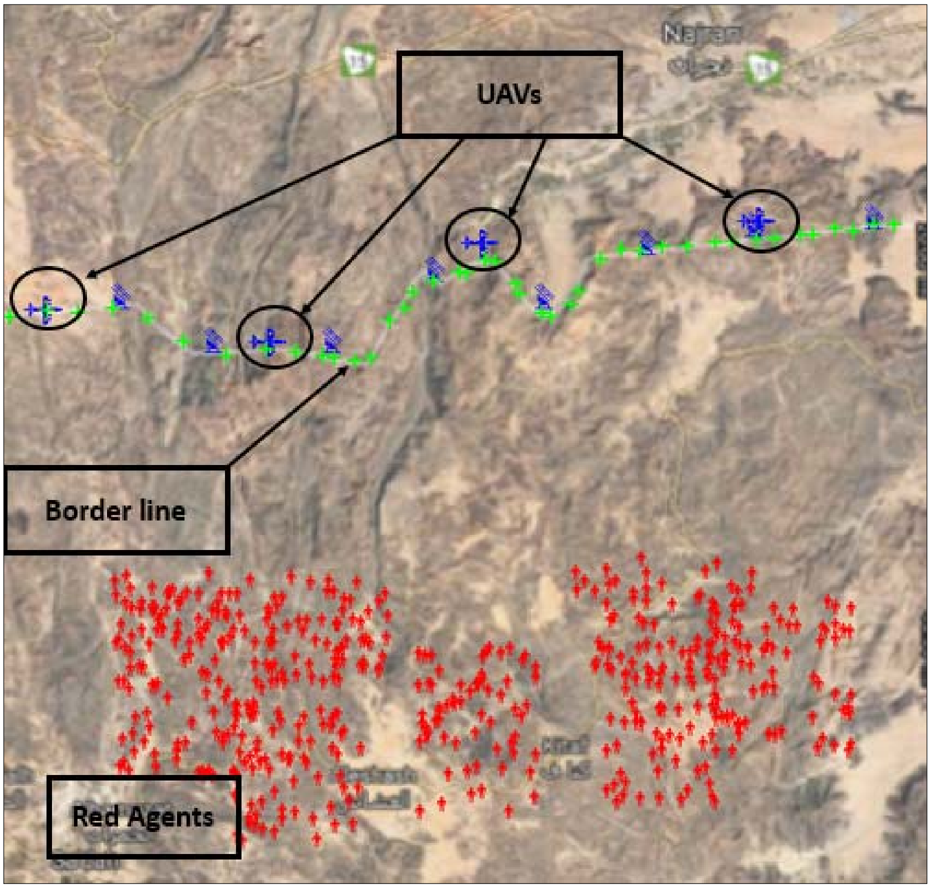


Figure 6. Improved Configuration Snap Shot with Four UAVs Setup.

4. Summary of Scenario Description

Three different groups of entities are modeled in this thesis. These groups are red agents that represent the enemy; blue radars, which represent the current detection equipment used by the GCF; and finally, the blue UAVs, which represent the new detection means. There will not be any simulated combat in this study.

a. Red Agents

Red agents are Houthi militias and other terrorist group members trying to cross the border; they consist of ten groups of 50 members in each group. Their main objective is to reach the border and get close to the GCF. The red agents are located at the southern part of the operational area and are moving north towards Saudi-Yemeni border, at a walking speed of four kilometers per hour.

Red agents have a concealment level that allows them to hide from blue detection assets. The higher the concealment level, the better the red agents are at staying away from detectors. In addition, they can increase their camouflage by using terrain paths, for instance, by traveling off roads or in mountains that have higher concealment levels than roads. Blue force radars along the border or the UAVs can detect red agents at any time during the operation. When red agents are detected, detection timing information will be recorded.

b. Blue Agents

Blue radars across the border have maximum range and detection capabilities. Nonetheless, some of the radars have limited detection because of the topography of the scenario, which may prevent blue radars from detecting red agents. Blue UAVs will jointly perform detection of red agents along with blue radars. Each simulation run represents 24 hours of the operation.

D. DESIGN FACTORS AND EXPERIMENTAL DESIGN

Designs of experiment (DOE) are used to examine the relationship and effects of different factors that might influence the outcomes of the MOE. Every factor in the DOE

has a range of values. The author has used analogous operational systems to estimate the appropriate range of values used in the DOE. In this thesis, a DOE helps to identify factors that have the largest effect on the MOE. The DOE further assists in reducing the variance of MOE estimates.

Jack Kleijnen et al. (2005) describe the DOE as a method that permits the user to vary input parameters to produce multiple variations in the model in an effective way. The DOE technique is used to determine the cause and effects bond, which is necessary for the selection of the inputs to enhance outcomes. Douglas Montgomery (2008) states that a design of experiment is a test where changes are made to the input variables on purpose, so we can observe the reasons for a change in the outcomes.

Factors can be categorized as controllable and uncontrollable factors. Controllable factors are those elements of the system that can actually be changed by the manufacturer or operators. The maximum flight altitude or speed, for example, are controllable factors. Uncontrollable factors are the factors that the designer cannot change in real life but can change during the experiment. Enemy characteristics and numbers are some examples of uncontrollable factors.

1. UAV

The UAV factors were selected based on Group 1 to Group 3 UAV technical characteristics (see Table 2), since this type of UAV category fits the required mission in detection and border control (United States Army 2010). Other UAV groups were eliminated for two reasons: they fly at a strategic high altitude level that is not required for this research, and their operating radius is very large.

The number of UAVs (one to four UAVs) is a design factor that will be crossed with the base experimental design. The UAV number factor will determine the minimum number of UAVs needed to achieve the required thresholds in the operation area.

- UAV speed is a flight performance factor that applies to the UAV. The UAV speed refers to the velocity the UAV travels at during the search mission.

- UAV altitude is another flight performance factor that defines the height that the UAV can fly in the covered area.
- Endurance is the ability of the UAV to fly without the need to refuel. It defines the UAV's stamina.
- UAV detection range is a sensor related factor that defines the maximum distance at which the sensor can detect targets.
- Time between detections is a factor that sets the period between "looks" at a search area. It defines how the UAV detects an object in the search area.
- Slew rate is the factor associated with how many degrees the UAV sensor can rotate per second.
- Aperture is the angle width that the sensor can search at each point of the rotation.
- UAV refuel time is the time it takes the UAV to be refueled and prepared for flight. This factor should reflect lower values, as it will have a negative effect on the availability of the UAV. The more time UAVs spend refueling, the higher their absence rate.

2. Red Agent

Red stealth is an uncontrollable factor. It represents the ability of the red agent to avoid being detected by radars or UAVs. Uncontrollable factors are introduced into models to reflect a real-life source of variations, which increases the credibility and robustness of outcomes of this study.

3. Factor Ranges

Factor ranges have been defined based on the possible UAV types that could be employed in the Decisive Storm operation in Yemen by the GCF (United States Army 2010). Table 3 presents the factor ranges chosen for the experiment that are defined as significant factors and might have impact on the outcomes of the research. All of the factors were chosen based on UAVs described in open sources.

Table 3. Design of Experiment Factors and Ranges.

Agent	DOE factor	Min.	Max.	Units
UAV	Speed	80	200	Knots
UAV	Altitude	3000	8000	Meters
UAV	Maximum detection range	1000	4000	Meters
UAV	Time between detection	5	20	Seconds
UAV	Endurance	1	8	Hours
UAV	Refuel time	30	60	Minutes
UAV	Slew rate	60	360	Degrees
UAV	Aperture	60	120	Degrees
Red forces	Red stealth	65	85	Percentage
UAV	Number of UAVs	1	4	Discrete

E. PREPARING MANA SOFTWARE FOR SIMULATION

MANA software is used as the simulation modeling software due to the ease with which the user can create scenarios and modify agents' properties. MANA has the ability to model the behaviors of the agents to a higher resolution. Another reason to use MANA is to take advantage of the Simulation Experiments and Efficient Designs (SEED) center at the Naval Postgraduate School (NPS), which offers scenario development support and data analysis, as well as a power-computing cluster that can perform complex and multiple factor levels simulations.

1. Data Entry and Control

A database is created in MANA to store entities' values required for the scenario. These values control the behavior of and set the limitations for entities in the simulation. MANA has the ability to store different types of maps to define the agent's movement in the simulation.

2. Battlefield

An area of 90 x 90 km along the Saudi-Yemeni border was chosen to represent the operational area. This area was modeled in MANA, with relevant entities, to represent the GCF military operations in Yemen. The battlefield area is a restricted military zone and divided into two sections. The northern part is the Kingdom of Saudi Arabia, where the

GCF are located. The southern part is a rugged area where Houthi militias and terrorist group members make their way towards the border. As previously mentioned, the military restricted area excludes not only military personnel, but also civilians or neutral personnel. Any detection in this area will be considered a target that the GCF will treat as a threat.

The border is defended by multiple radar systems to detect infiltrators and report the detection back to the GCF operation centers to deal with the infiltrators. Figure 7 represents the battlefield agent's locations and the border area.

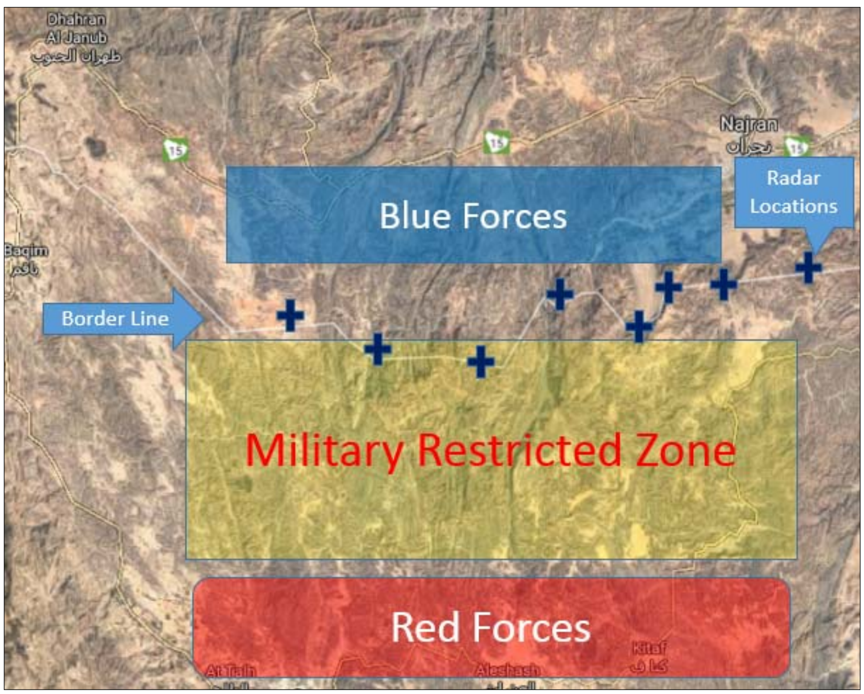
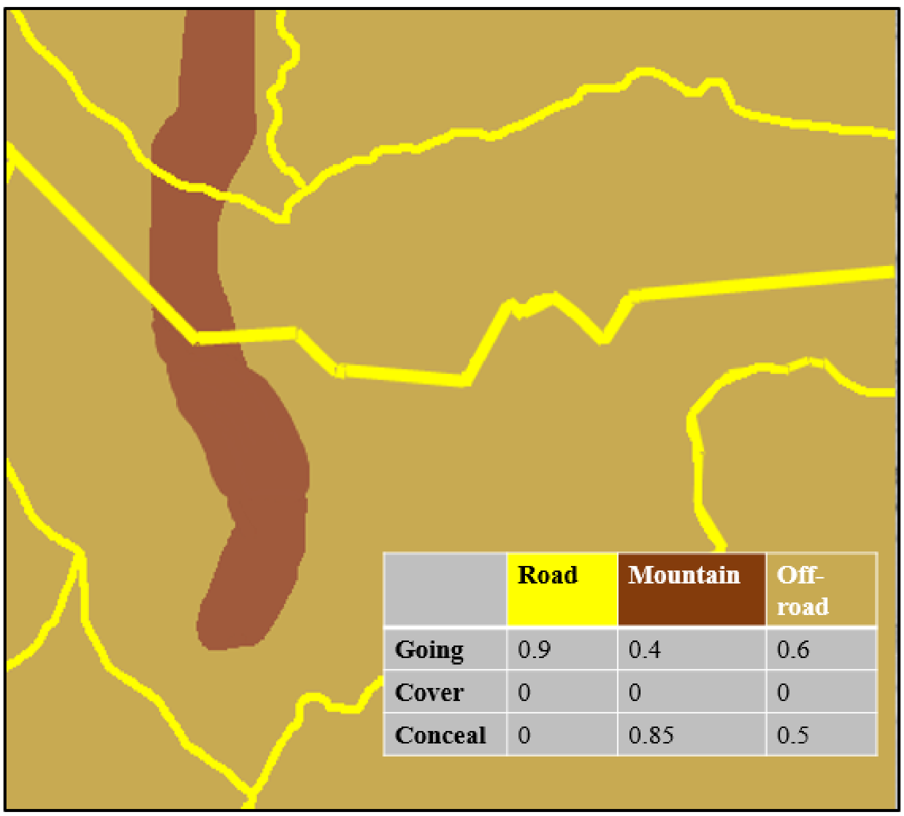


Figure 7. Battlefield Description and Entities Locations.

3. Map Construction

MANA can store elevation, terrain, and background maps to define the agent movement in the scenario. The difference in elevation heights can act as a concealment factor for the agent that increases the stealth of the agent, or restrict the movement of the agent towards its goal. It also plays a role in the line of sight (LOS) factor for the sensors that may delay the detection time.

The terrain features map was constructed in MANA to reference the elevation areas. It consists of three different levels: mountains, off roads, and valleys. To ensure the ground radars and UAV sensors operate properly, it is imperative to define these levels in the model. Figure 8 shows the terrain map with the terrain characteristics levels of going, cover, and concealment, as well as the terrain surface levels of road, mountain, and off-road. “Going” refers to the level of movement; “Conceal” is the visibility level; and “Cover” is the protection level the agent could have. Those three levels range from zero to one. Zero means “No” and one means “Full.” For example, when an agent uses the “Road,” he has ease of movement, but no cover or concealment against detection. While in the mountains, the agent has a high level of concealment or a good chance to avoid detection, but difficulty in movement.



	Road	Mountain	Off-road
Going	0.9	0.4	0.6
Cover	0	0	0
Conceal	0	0.85	0.5

Figure 8. Terrain Features Map and Parameters.

F. DESIGN OF EXPERIMENT

Examining all factors listed in Table 3 requires a time-efficient design of experiment technique to cover all factors and to effectively and uniformly sample the design space. A full factorial experiment is one option that requires an extended period to complete. A full factorial design for this thesis will produce 170 million design points, which would require more than five years to process if each run took one second to complete. While the author desires a thorough exploration of design space for this research to assure discovering important insights, this amount of time is impractical. Susan Sanchez and Hong Wan (2015) explain that experiments should be designed in a keen manner by using a well-organized space filling design, which this research accomplishes, as the following discussion describes.

1. Nearly Orthogonal Latin Hypercube Design Method

In lieu of a full factorial design, we are going to use the nearly orthogonal Latin hypercube (NOLH) 65-design point method developed by Thomas Cioppa and Thomas Lucas (2007). NOLH design is a method used to combine orthogonal and uniform designs to create efficient, uncorrelated, fully space-filling experiments (Cioppa and Lucas, 2007). It significantly decreases the number of design points (DP) in the experiment compared to a full factorial design. For these reasons, we chose an NOLH design. This type of design also works best when design factors are continuous values such as those listed in Table 3.

An NOLH spreadsheet created by the NPS SEED center (n.d.) was used to generate a unique combination of factor levels for this thesis. A 65-run NOLH design to explore the factors in Table 3 provides good coverage of the possible combinations in the input space. Crossing the 65 DP with the number of UAVs in the improved configuration yields 260 different design points (see Appendix A).

The scatter plot in Figure 9 shows the pairwise plots between factors in the experimental design. It shows the space-filling attributes of the NOLH in the two-dimensional space. If it were possible to create plots for all other dimensions, they would

present similar graphics. They depict a design that effectively and efficiently samples the problem space.

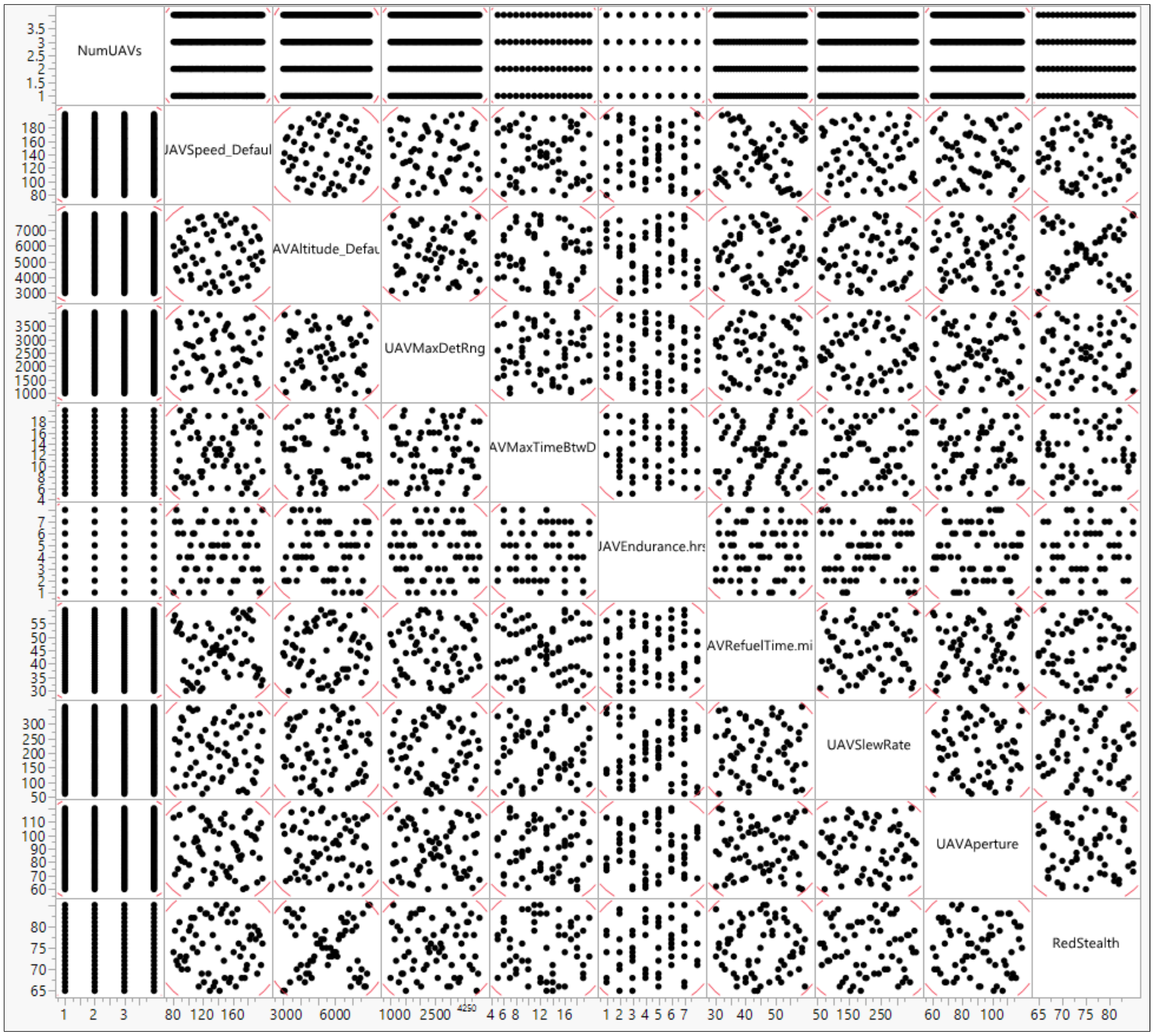


Figure 9. Scatterplot Matrix All Factors.

2. Number of Replications

Each design point has to be replicated to reduce the variability of the estimate of the MOE's outcome. Replication deals with the random errors in the experiments. For the purpose of this thesis, we have selected a 95% confidence interval of the estimated mean for the MOEs. This value of confidence interval was chosen to create the desired interval width of approximately three agents for MOE 1 and approximately eight minutes for

MOE 2. From the operations perspective, the author asserts that these are within the margins that the GCF can effectively operate. Therefore, determining the required number of run replications is important if we are to reach the desired degree of precision in the results.

We determined the number of replications according to the formula that takes into account our estimate of the standard deviation (σ) and our chosen level of alpha (α = 0.05). Z is the variant corresponding to half of alpha, based on the standard normal distribution. The desired width of the confidence interval for a probability is *w*.

$$n = \left(\frac{2Z_{\alpha/2}\sigma}{w} \right)$$

Forty replications per design point were sufficient for both MOEs. MOE1 needed 33 replications while MOE2 required 40 replications. Therefore, we chose to run each design point 40 times. Additionally, this number of replications allows the experiment to finish in a reasonable time. The mean of each 40 replications is ultimately summarized and used for the data analysis (see Appendix B).

IV. DATA ANALYSIS

This chapter contains results answering the research questions and illustrating how UAV technology can improve the detection capability for the GCF. Sensitivity analysis results are used to examine the model and determine whether the system is sensitive to scenario parameters such as the specific number of red agents trying to cross the border. Next, a baseline configuration analysis demonstrates the percentage of detected red agents the current system provides in the operation. Third, scenario analysis and comparison with the baseline results test whether UAVs will provide an additional percentage of red agent detection. Fourth, a regression analysis allows us to understand which factors are significant. Finally, relative cost and benefit analyses provide an understanding of the relative cost of various options.

A. SENSITIVITY ANALYSIS TO RED AGENT SCENARIO

The purpose of the sensitivity analysis is to examine the consistency of the model outcomes with different attack scenarios in place. Figure 10 shows the distribution of the total number of red agents detected, percentage of red agents detected, and time to detect 40% of red agent using the improved configuration with four UAVs. Two different quantities of red agents, 50 and 500, have been used to compare the distribution between the two formations.

Results show that the average number of red agents detected using the 500-agent formation equals 406, while the 50-agent formation average scored 41. Second, the average percentage of red agents detected for the 500 formation was 81% with a 1% increase in the 50-agent formation. Finally, the average time to detect 40% of the red agents was 6.8 hours for the 500-agent formation, while the 50-agent formation took seven hours.

Results show that distribution and summary statistics are very similar for both scenario configurations and the outcomes are not contingent on a specific scenario or a certain number of red agents. These statistics increase the author’s confidence in the model results and potential biases in the data.

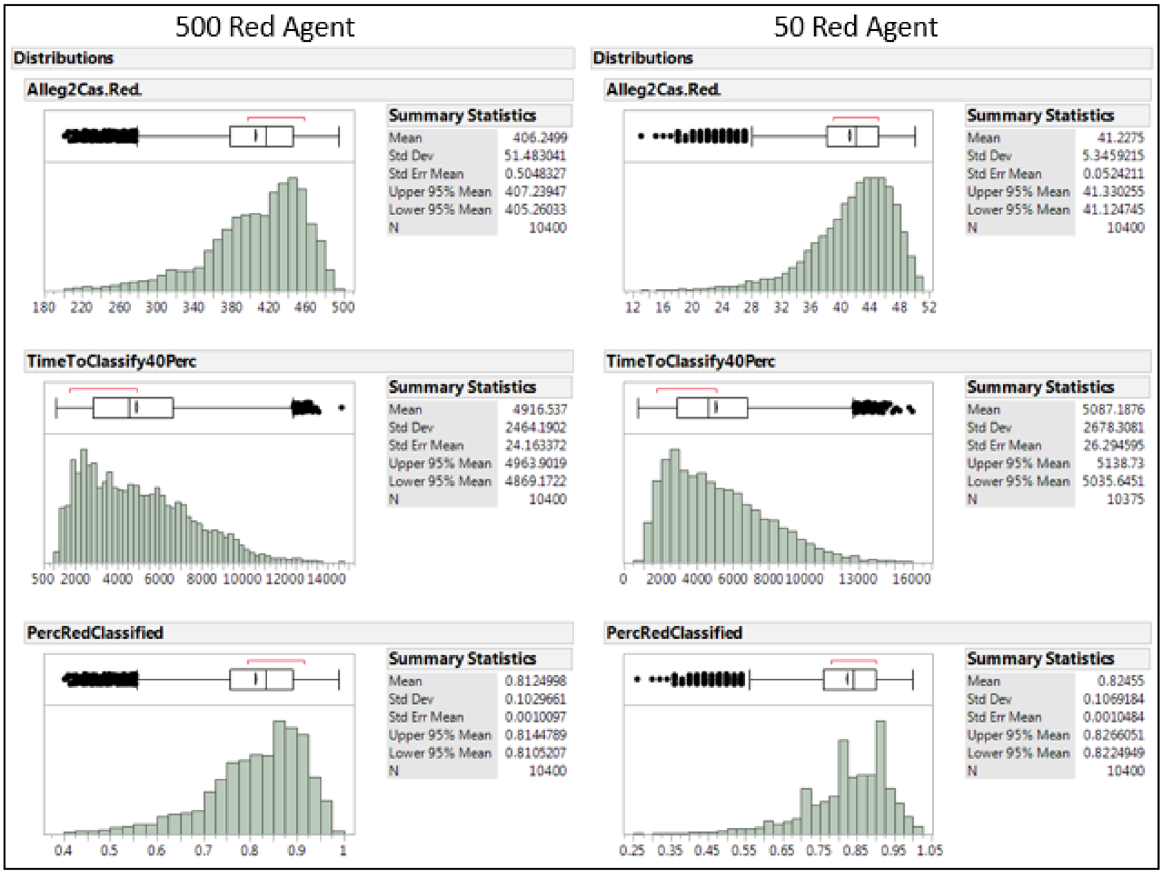


Figure 10. Sensitivity Model Analysis.

B. RESULTS OF BASELINE CONFIGURATION (GROUND RADARS ONLY)

1. Desired Percentage of Red Agents Detected

To define the GCF baseline capability, we are trying to find the right combination of ground radars such that we detect only 30% of the red agents. Three radar factors are examined using an NOLH method to determine the combination of the blue radar factors that can achieve the desired percentage of red agents: Number of radars, Maximum detection range, and Time between detection.

Sixty-five different combinations across the three factors have resulted in the material depicted in Appendix C. The results show that combinations with a low number of radar stations (from four to six) were not able to provide the desired percentage of red

agents detected. Therefore, they are disregarded. Combinations with seven or eight radars were able to generate results approximating the desired percentage of red agents detected.

The highlighted design factor (No# of radars=8, Time b/w detection=108, and max range of 5625) came closest to the desired baseline percentage of red agent detection, registering a score of 30.35% (Table 4). We have rounded them up to (No# of radars=8, Time b/w detection=100 seconds, and max range of 6000 meter) to ensure it will generate detection of at least 30% of the red agents. Among all other possible combinations, we use those values as the baseline for this study because those values seem to have the characteristics of operational understanding of the situation.

Table 4. Blue Radar Design Points for the Desired Percentage of Red Agent Detections (7 and 8 Radars Only).

NumBlueRadars	BlueRadarRng	BlueRadarAvgTimeBetDet	Std Dev(Alleg2Cas.Red.)	Mean(PercentageRedDetected)
7	6313	93	8.859443752	0.3537
7	5750	83	8.208813275	0.348
8	5188	68	7.361542481	0.3375
8	6063	101	8.230493645	0.3349
7	7063	115	9.272201354	0.33405
8	6625	116	8.738215508	0.3301
7	5000	66	9.185237599	0.32825
7	5563	94	7.445141248	0.31965
8	5625	108	8.619447302	0.3035
8	5438	117	8.556898552	0.2872
7	4813	84	8.318615208	0.28615
7	4125	61	9.106070109	0.2849
7	4750	92	9.448884075	0.28095
7	4188	82	9.508397099	0.25945

2. Baseline MOE 1 Percentage of Total Red Agents Detected

Figure 11 represents the distribution of the percentage of red agents detected for the selected baseline values. The detection percentage was attained by averaging the outcomes of 100 repetitions of the baseline design point. An average of 32.19% of red agent ± 2.1% was detected at a 95% Confidence Interval (CI), which is lower than the required MOE 1 threshold of 90% of red agents detected.

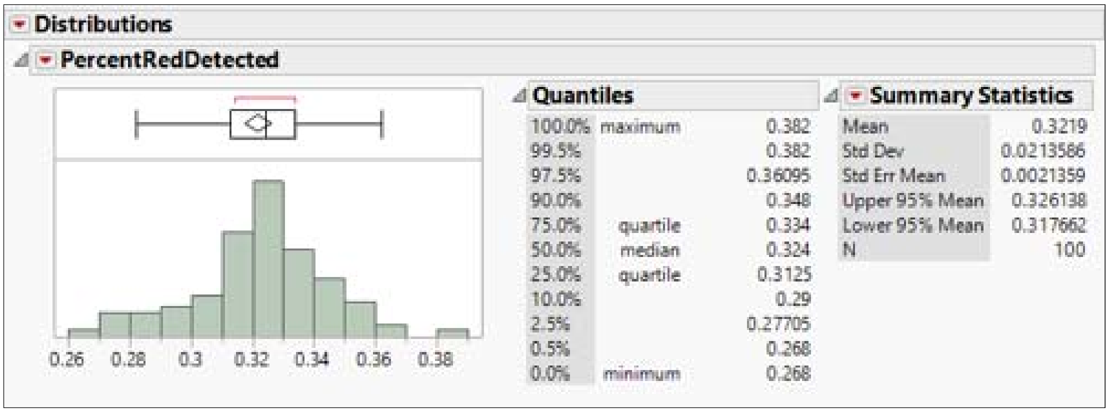


Figure 11. Distribution and Summary Statistics for Baseline Configuration (MOE 1).

C. RESULTS OF THE IMPROVED CONFIGURATION (GROUND RADARS WITH ONE OR MORE UAVS)

1. MOE 1: Percentage of Total Red Agents Detected

Figure 12 represents the distributions of the percentage of red agents detected when the ground radars, along with the one or more UAVs, are implemented in the improved configuration. An average of 81.24% of red agents ± 1% was detected at a 95% CI, which is less than the required MOE 1 threshold of 90% of red agents detected.

The implementation of UAVs in the operation for the GCF shows an increase of detection by almost 49%. The important factors that led to this increase are discussed in later sections.

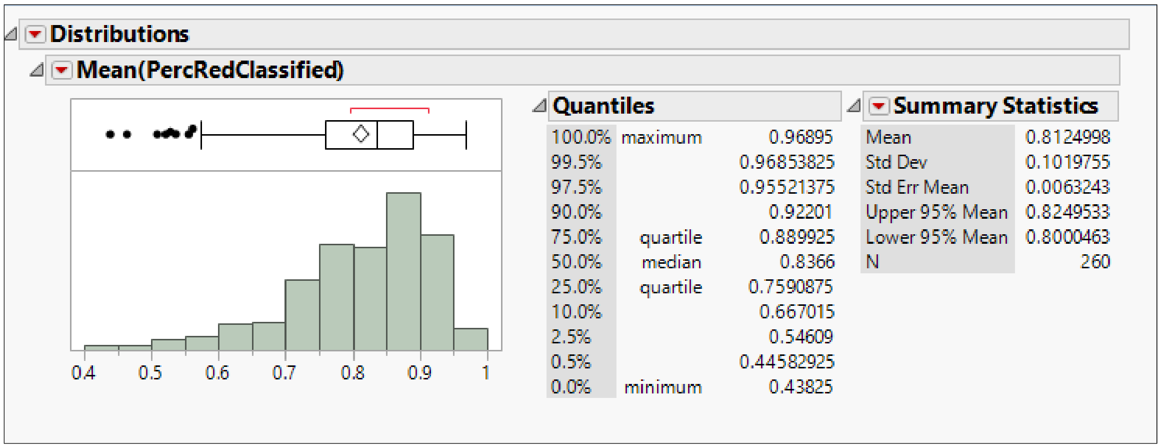


Figure 12. Distribution and Summary Statistics for Improved Configuration (MOE 1).

2. MOE 2: Time It Takes to Detect 40% of the Red Agents

Figure 13 shows the total time it takes to detect 40% of the red agents in the operation. Adding the UAVs will benefit the GCF by speeding up the process of detecting the red agents, allowing GCF to determine the center of activity to pursue. This will enhance the probability of successfully securing the border.

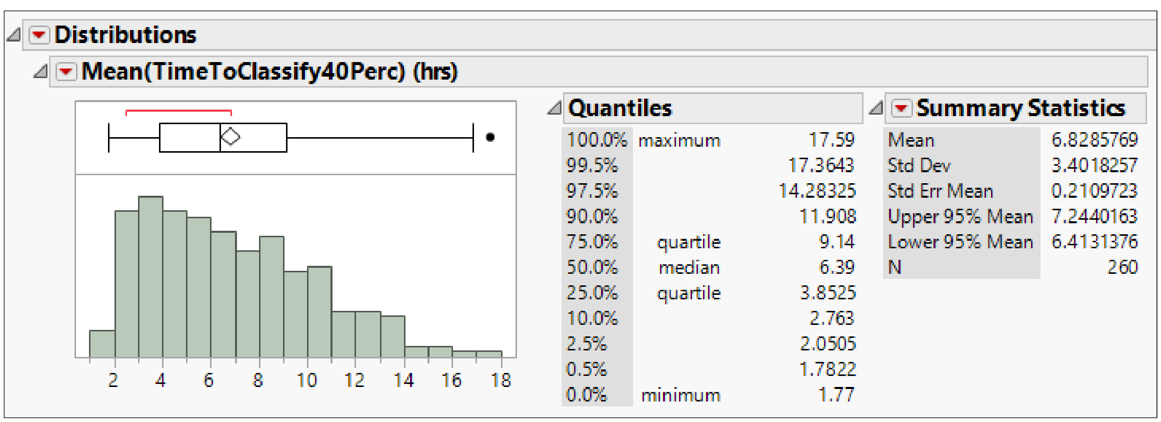


Figure 13. Distribution and Summary Statistics for Improved Configuration (MOE 2).

The data distribution for MOE2 shows a non-symmetrical distribution (Figure 13). An average time of 6.8 hours to detect 40% of the red agents has been achieved. This

average mean value lands around the 65th percentile in the distribution, which means 35% of the data can detect the red agents in shorter periods.

The introduction of the UAVs, along with the available ground radars, has apparently improved the speed of the detection in comparison with the baseline configuration, but it still did not meet the threshold value of the MOE 2 (3.55 hours).

3. Conclusion for the Improved Configuration

The introduction of the UAVs with their current capabilities, along with the available ground radars, has significantly improved the percentage of red agent detection and the time to detect them, but it did not achieve the required threshold for either of the MOEs. This means that there should be further investigation into what improvement in UAV capabilities (United States Army 2010) will increase the percentage and speed of detection. This investigation will aid the GCF's decision in what specific capabilities they should invest.

D. EXAMINATION OF THE UAV'S SIGNIFICANT CAPABILITIES

We claim that a specific number of UAVs with certain capabilities will achieve the required threshold for both MOEs for the GCF to accomplish mission success. The next section examines the possible combination of UAV capabilities that could succeed.

Introducing the UAV technology to support the detection for the GCF has shown apparent improvement, but it did not reach the specified operational goals. Thus, the next section considers the method of determining what particular UAV characteristics are most valuable. First, we plot the correlation between the two selected MOEs to better observe whether one or more design points can satisfy both MOEs. Second, we examine the significant factors that have the greatest impact on the UAV through regression analysis. Third, we use a partition tree analysis to identify the design point options that can meet both MOEs. Finally, we perform a relative cost and benefit analysis to discover the desirable design point option.

1. Correlation between MOEs

The two MOEs are correlated when shown graphically (Figure 14). The graphical presentation helps to identify possible design points that could satisfy the operational requirements for the GCF. Figure 14 shows a scatter plot between the two MOEs with their threshold levels and possible DPs that can achieve mission success. As shown in Figure 14, multiple DPs fall within the operational goal target, represented by the shaded area.

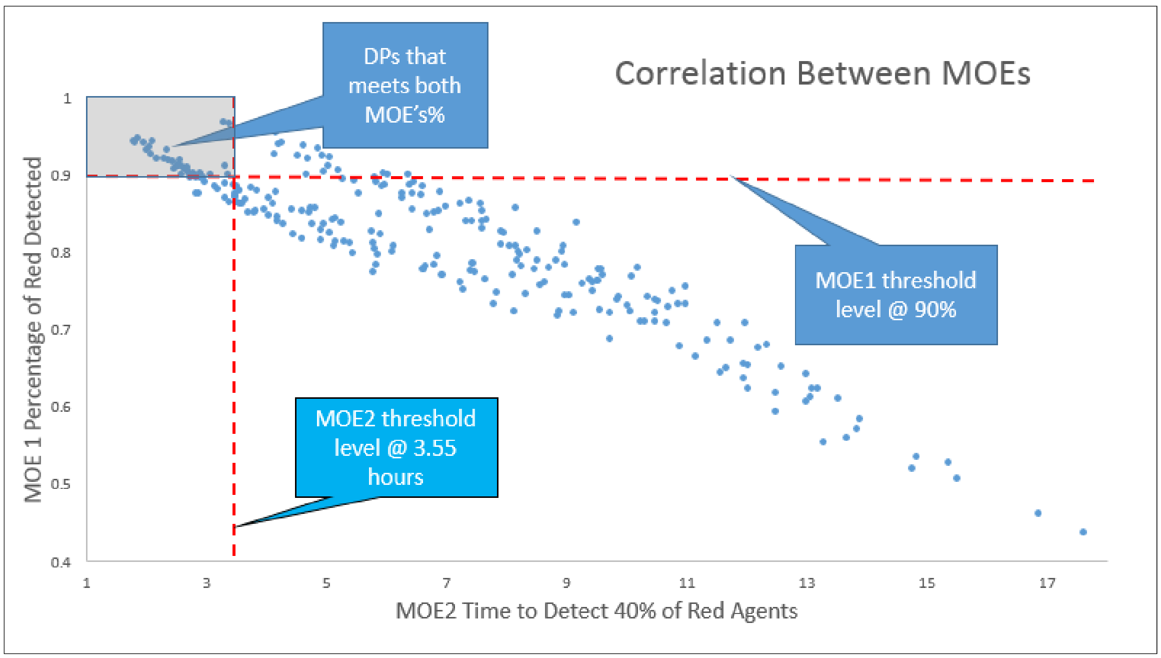


Figure 14. Correlation between MOEs.

2. Significant Factors Selection

Identifying the most significant factors of the UAV will help the GCF identify the UAV best suited for the required detection mission. Examining the factors will help in focusing on only those factors related to improving the detection capability of the UAV. We use regression analysis to discover the significant factors for the UAV.

a. MOE 1 Significant Factors

A 10-factor stepwise linear regression model results in an adjusted R square value of 0.68, which indicates that the regression model developed is adequate to predict the behavior of MOE 1. The stepwise regression analysis examines how much each of those factors can add to the description of the MOE 1, which will identify the important factors. This first step screens all significant factors for MOE 1. We do not consider interaction terms in this regression model. Figure 15 lists all the factors with the largest effect on MOE 1.

Sorted Parameter Estimates

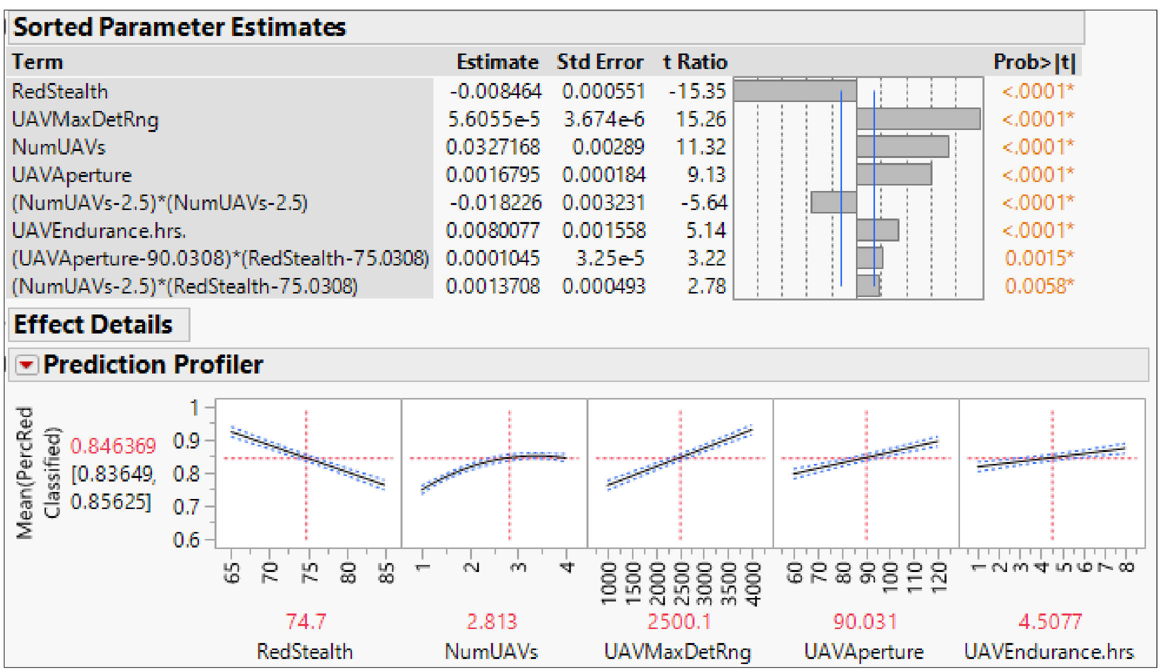
Term	Estimate	Std Error	t Ratio	Prob>|t|
RedStealth	-0.00847	0.000602	-14.08	<.0001*
UAVMaxDetRng	5.6129e-5	0.000004	14.00	<.0001*
NumUAVs	0.0327168	0.003152	10.38	<.0001*
UAVAperture	0.0016761	0.000201	8.35	<.0001*
UAVEndurance.hrs.	0.0078887	0.001703	4.63	<.0001*
UAVAltitude_Default	-3.593e-6	2.405e-6	-1.49	0.1365
UAVMaxTimeBtwDet	-0.000911	0.000798	-1.14	0.2545
UAVSlewRate	-2.317e-5	4.012e-5	-0.58	0.5641
UAVSpeed_Default	-2.948e-5	0.0001	-0.29	0.7690
UAVRefuelTime.min.	3.1134e-5	0.000399	0.08	0.9379

Figure 15. Significant Factors for MOE 1.

The significance level (α) was selected to be 0.05, which is the limit to reject or fail to reject a factor. The t Ratio value is a test statistic for the hypothesis test to evaluate whether the estimate for that factor is significant. Patrick Runkel (2016) in his blog section T & P explains that "t-value measures the size of the difference relative to the variation in the sample data. It is the calculated difference represented in units of standard error." The greater the t-value, the greater the evidence to reject the null hypothesis to which the associated population parameter is plausibly equal. The null hypothesis is that the true value of the coefficient related to the factor is 0; indicating that it has no influence on the MOE.

The estimate value in the second column is the amount of change to MOE 1 per one unit change in the factor–the estimated coefficient. For example, the red stealth estimate has a negative value of (-0.00847) because as red stealth increases one unit, the percentage of red agents detected decreases by this value. Another case is the detection range factor. It can be explained as: for every 1-meter increase in detection range, MOE 1 increases 5.6e-5 percent.

A second order stepwise regression analysis was performed to find significant factors that interact with other factors. It results in an adjusted R square of 0.73, which indicates that the regression model developed is adequate to predict the behavior of MOE 1. Figure 16 shows the significant factors of the second order with their associated values. Five factors were significant as shown in the Prediction Profiler: Red Stealth, UAV Maximum detection range, Number of UAVs, UAV Aperture, and the UAV Endurance.



Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
RedStealth	-0.008464	0.000551	-15.35	<.0001*
UAVMaxDetRng	5.6055e-5	3.674e-6	15.26	<.0001*
NumUAVs	0.0327168	0.00289	11.32	<.0001*
UAVAperture	0.0016795	0.000184	9.13	<.0001*
(NumUAVs-2.5)*(NumUAVs-2.5)	-0.018226	0.003231	-5.64	<.0001*
UAVEndurance.hrs.	0.0080077	0.001558	5.14	<.0001*
(UAVAperture-90.0308)*(RedStealth-75.0308)	0.0001045	3.25e-5	3.22	0.0015*
(NumUAVs-2.5)*(RedStealth-75.0308)	0.0013708	0.000493	2.78	0.0058*

Figure 16. Second Order Stepwise Linear Regression for MOE 1.

The Prediction Profiler shows an interesting result: the Number of UAVs factor (as a main factor) shows that increasing the number of UAVs beyond three provides marginal improvement to MOE 1. This could be because three UAV sets saturate the

operational area and we do not need an extra UAV set. This factor requires further study on route development and sensor capabilities, but that is beyond the scope of this thesis.

Figure 17 shows a matrix of interaction between the factors. A non-parallel line gives an indication of possible interaction between the factors and their effect on that MOE. For example, the highlighted interaction between the UAV Aperture and Red Stealth factors can be explained as follows: when Red Stealth is low (Value 65), changing the UAV Aperture (from 60 to 130 degrees) has minimal effect on MOE 1. By contrast, when Red Stealth is high (Value 85), increasing UAV Aperture (from 60 to 130 degrees) has larger impact on MOE 1.

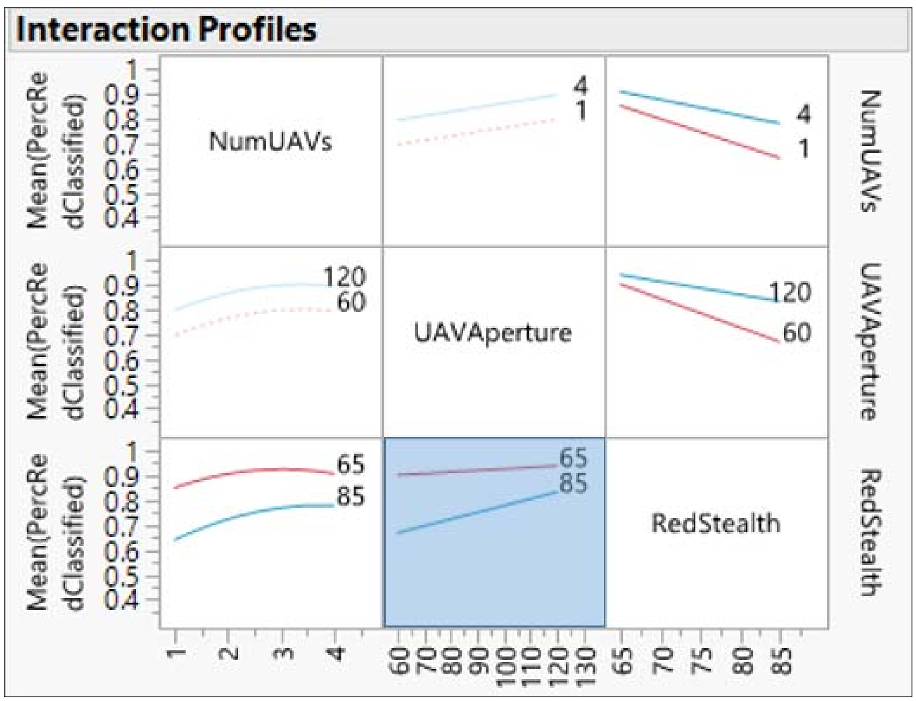


Figure 17. Factor Interaction MOE 1.

b. MOE 2 Significant Factors

Another 10-factor linear regression model was conducted for MOE 2 that results in an adjusted R square of 0.80, which indicates that the regression model is adequate to predict the behavior of MOE 2. With the same significance level selected for MOE 1 of 0.05, Figure 18 shows, in order of importance, the significant factors that have an impact

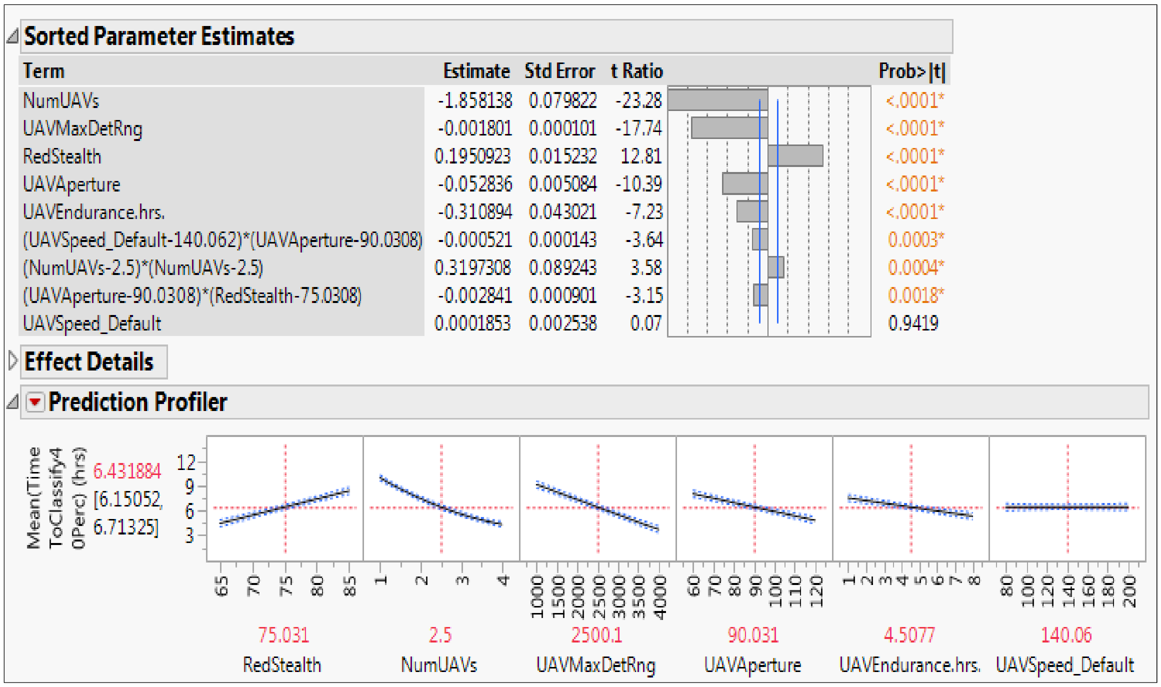
on MOE 2. As seen in Figure 18, five factors have an impact on MOE 2. The Estimate value for the number of UAVs factor shows a negative value, which means that as the number of UAVs increases, the time it takes to detect 40% of the red agents decreases. Similarly, in the UAV endurance factor, the greater the UAV endurance means the less time we need to detect 40% of the red agents. This is because the UAV will not waste time when refueling on the ground and will spend more time in the air. The Red Stealth factor, on the other hand, shows a positive value, which reflects the following: as the red stealth level increases, the time it takes to detect the red agents increases as well.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
NumUAVs	-1.858138	0.084219	-22.06	<.0001*
UAVMaxDetRng	-0.001803	0.000107	-16.84	<.0001*
RedStealth	0.1952902	0.016078	12.15	<.0001*
UAVAperture	-0.05267	0.005364	-9.82	<.0001*
UAVEndurance.hrs.	-0.306637	0.045507	-6.74	<.0001*
UAVAltitude_Default	0.0001244	6.427e-5	1.94	0.0541
UAVMaxTimeBtwDet	0.0287277	0.021321	1.35	0.1791
UAVSlewRate	0.0007187	0.001072	0.67	0.5032
UAVRefuelTime.min.	-0.004073	0.010664	-0.38	0.7028
UAVSpeed_Default	0.0003005	0.002679	0.11	0.9108

Figure 18. Significant Factors for MOE 2.

Performing a second order stepwise regression model has resulted in a higher adjusted R square value of 0.82 and an additional factor that might have an impact on MOE 2. Figure 19 illustrates the significant factors of the second order with their associated values.



Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
NumUAVs	-1.858138	0.079822	-23.28	<.0001*
UAVMaxDetRng	-0.001801	0.000101	-17.74	<.0001*
RedStealth	0.1950923	0.015232	12.81	<.0001*
UAVAperture	-0.052836	0.005084	-10.39	<.0001*
UAVEndurance.hrs.	-0.310894	0.043021	-7.23	<.0001*
(UAVSpeed_Default-140.062)*(UAVAperture-90.0308)	-0.000521	0.000143	-3.64	0.0003*
(NumUAVs-2.5)*(NumUAVs-2.5)	0.3197308	0.089243	3.58	0.0004*
(UAVAperture-90.0308)*(RedStealth-75.0308)	-0.002841	0.000901	-3.15	0.0018*
UAVSpeed_Default	0.0001853	0.002538	0.07	0.9419

Figure 19. Second Order Stepwise Linear Regression MOE 2.

The UAV Speed as a main factor has no effect on MOE 2 as shown in the Prediction Profiler (almost flat curve line), but it will have an effect when interacting with other factors (Figure 20). The interaction matrix for the MOE 2 significant factors shows an interaction between the UAV Speed factor and the UAV Aperture factor over MOE 2. When the Speed of the UAV is high (value = 200), increasing the UAV Aperture (from 60 to 130 degrees) has a larger impact on MOE 2.

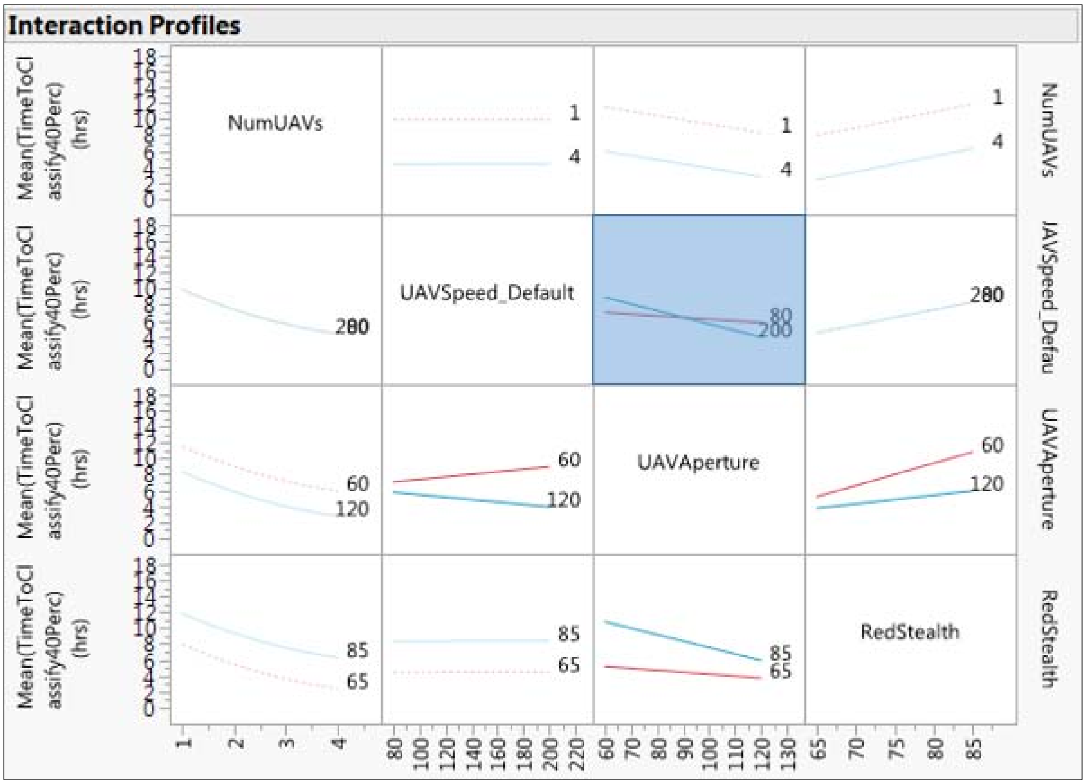


Figure 20. Factor Interaction MOE 2.

As a result of this interesting finding about the interaction between factors, we decide to use the UAV Speed as a significant factor. Therefore, a total of six factors were significant for MOE 2: Red Stealth, UAV Maximum detection range, Number of UAVs, UAV Aperture, UAV Endurance, and UAV Speed.

c. Major Significant Factors

While MOE 2 has the UAV Speed as an additional significant factor that influences it, the two MOEs have five of the factors in common. Thus, a total of six factors have a significant effect on the UAV's ability to improve GCF's capability to detect and respond to infiltrators.

3. Design Points that Meet Both MOEs

We plotted the correlation between the MOEs in Figure 14 and highlighted the intersection area of design points that meet the threshold level of both MOEs. A total of a 32 design points met the criteria and are used for further analysis (Table 5).

Table 5. Design Points that Meet MOE 1 and MOE 2.

No#	DP	NumUAV	UAVSpeed	UAVAltit	UAVMaxDetecRange	TimeB/wDetec	Endurance	RefulTime	SlewRate	Aperture	RedStealth
1	**79**	2	149	4641	3344	19	4	37	201	116	68
2	**106**	2	118	7844	3953	8	5	42	243	114	69
3	**110**	2	134	6906	3016	10	5	45	304	103	66
4	**140**	3	142	3078	3906	13	2	43	154	101	65
5	**141**	3	198	5578	3063	19	2	32	173	109	71
6	**144**	3	149	4641	3344	19	4	37	201	116	68
7	**150**	3	179	4016	2219	6	8	41	65	102	71
8	**159**	3	164	7688	2031	16	7	60	163	92	66
9	**163**	3	114	7766	2922	15	7	37	121	91	66
10	**171**	3	118	7844	3953	8	5	42	243	114	69
11	**172**	3	84	4563	2547	9	8	52	83	98	72
12	**175**	3	134	6906	3016	10	5	45	304	103	66
13	**176**	3	106	5266	2734	7	6	31	346	120	75
14	**201**	4	172	3938	2594	5	3	40	327	85	68
15	**205**	4	142	3078	3906	13	2	43	154	101	65
16	**206**	4	198	5578	3063	19	2	32	173	109	71
17	**209**	4	149	4641	3344	19	4	37	201	116	68
18	**211**	4	183	5188	2172	7	6	60	294	118	77
19	**212**	4	148	7297	1797	10	5	44	308	108	72
20	**215**	4	179	4016	2219	6	8	41	65	102	71
21	**221**	4	181	3469	3250	17	5	57	158	117	80
22	**224**	4	164	7688	2031	16	7	60	163	92	66
23	**226**	4	185	6281	3813	18	6	49	332	100	78
24	**227**	4	140	5500	2500	13	5	45	210	90	75
25	**228**	4	114	7766	2922	15	7	37	121	91	66
26	**229**	4	86	4406	3672	14	6	53	196	75	71
27	**233**	4	136	3391	3297	13	7	40	318	68	67
28	**236**	4	118	7844	3953	8	5	42	243	114	69
29	**237**	4	84	4563	2547	9	8	52	83	98	72
30	**240**	4	134	6906	3016	10	5	45	304	103	66
31	**241**	4	106	5266	2734	7	6	31	346	120	75
32	**246**	4	112	6047	2313	16	3	33	351	96	74

4. Partition Tree Analysis

We use a partition tree analysis to find the most consistent or predictable way to satisfy both MOEs. This method enables us to explain the predicted value through a multiple combination of factors. The partition tree moves from top to bottom, searching for possible splits between factors, and it indicates the best split, based on greater values.

The graphical tree structure provides an easy way to understand and interpret data. It allows for discovering a correlation between factors in the data. Readers should note that every design point (DP) is a mixture of different factor levels (refer to Table 5), and each DP is one UAV possible option.

a. Partition Tree Analysis for Both MOEs

To improve the detection capability for the GCF and increase border security, we aim to meet both MOE thresholds. As discussed in the Design Point section, 32 DPs out of 260 satisfied the criteria of both MOEs.

The following description is a simplified version of the tree analysis on which factors contribute most to satisfying both MOEs. For more detailed analysis with exact values, please refer to Appendix D.

The partition tree in Figure 21 represents the breakdown of the overall (260) design points. The top box contains the DPs that met both MOEs (32 DPs) marked with "YES." The first split appears on the red stealth level. Splitting the tree with the Red Stealth factor can assist the GCF in determining the ideal UAV in extreme cases for detecting red agents when they are most and least capable of being detected.

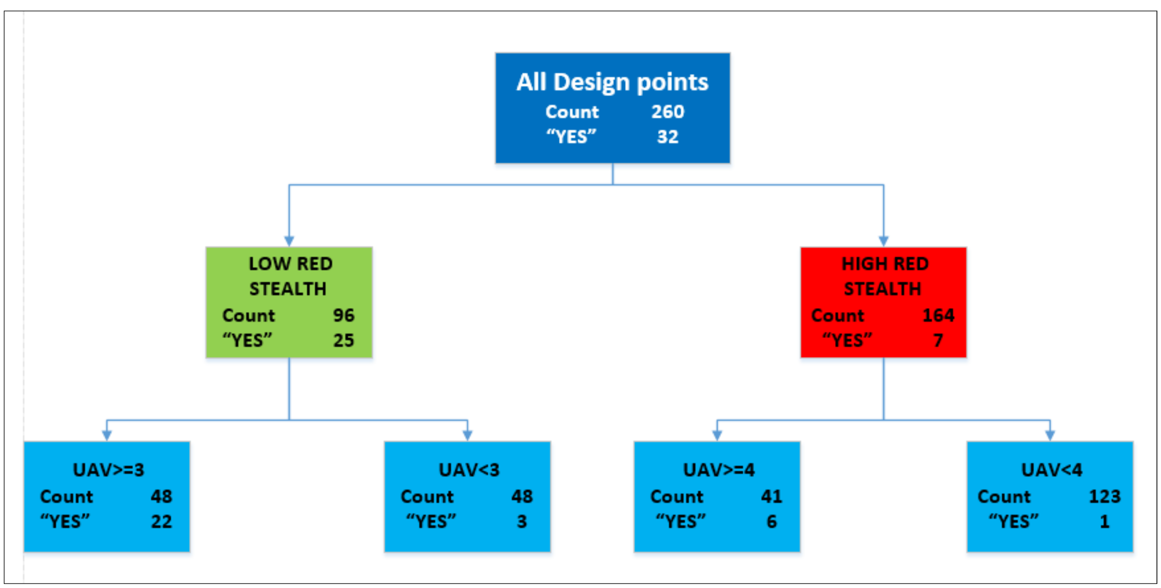


Figure 21. Partition Tree for MOEs.

As the split on this level indicates, the Low Red Stealth factor has 96 DPs among the 260, but only 25 of them can achieve both MOEs. The High Red Stealth factor has 164 DPs out of 260, but only seven can meet the MOEs' criteria.

We further split the tree to see how the UAV factors contribute to the success in the low and high red stealth cases. The next split under the low stealth cases is based on the number of UAVs, which splits evenly: 48 DPs on both sides. The "YES" criteria was achieved 22 times when the number of UAVs was three or more, while it was achieved only three times when UAVs were fewer than three.

The high red stealth path shows seven possible DPs that can achieve both MOEs. Only one DP can possibly meet both MOEs with less than four UAVs. The other six DPs require four UAVs.

We can further split the tree to better analyze the data and better understand which factor will have an effect on the achievement of the MOE thresholds (see Appendix D).

b. Partition Tree Outcomes

Solutions using more UAVs tend to give better results or more options to achieve the MOEs' threshold, but the marginal improvement after the third UAV set does not appear to justify the cost. In the next section, however, we examine the benefit of an additional UAV in comparison to relative costs.

There are only a few design point options to examine when the enemy is highly stealthy. Seven DPs have achieved the threshold for both MOEs in the high red stealth configuration. One of those DPs can meet both MOE thresholds with less than four UAVs.

In the other scenario when the enemy is less stealthy, 25 design point options achieved the threshold for both MOEs. Using at least three UAV sets appears to provide more options to detect at least 90% of the red agents in 3.55 hours or less. The partition tree in Figure 21 shows three design point options that meet both MOEs' thresholds using fewer than three UAV sets. Further experimentation follows in this thesis to show which DP option is the most cost-effective combination.

5. UAV Capability and Relative Cost Analysis Tradeoff

Following Sangbum Kim's (2017) approach to developing a relative cost analysis will help identify the best UAV capabilities at the most effective cost. Assigning each UAV capability with a value assists in computing each design point's final relative cost. The optimum design point should have a high MOE value and lowest relative cost. However, a UAV's component cost breakdown is unavailable and hard to obtain within the time frame of this thesis. Therefore, we create a relative cost scale for each UAV capability in terms of the user priorities to develop an estimate cost for each DP. A comparison between the DP final relative cost and its MOE value will aid in defining the option we desire to pursue.

To calculate the expected cost for each design option, we need a reference UAV model upon which to base our calculation. As mentioned in Chapter III, a UAV from Group 1 to Group 3 was used to set the factor ranges in this study. The Raven RQ-11 UAV (Figure 22) used by the U.S. military (Kasper 2014) falls into this category and is used as a cost reference for this study.

Figure 22. Raven RQ-11 UAV. Source: AeroVironment.inc (2017).

The estimated cost of the Raven RQ-11 is $300,000 USD for a set of three UAVs with the two ground control stations and its supporting equipment (Kasper 2014). The

price of one UAV vehicle is estimated at $34,000. The author has derived a price breakdown of the Raven RQ-11 system (Table 6).

Table 6. Author-derived Raven RQ-11 Cost Breakdown.

Raven RQ-11 Cost	$ 300,000
Vehicle Cost	$ 34,000
Vehicle Cost x 3 (Three vehicles)	$ 102,000
GCS (x 2) + Supporting equipment	$ 198,000

a. Factor Relative Cost Scale

The cost of each design point is a product of the UAV capability factor cost. Therefore, we need to compute the relative cost of the eight UAV capability factors. The Analytic Hierarchy Process (AHP) can aid in calculating UAV factor weights for this study.

The AHP process runs a pairwise comparison between the factors based on which factor has more importance in terms of UAV performance (Table 7). The more important the factor in regards to the UAV performance, the higher the relative cost it will have.

Table 7. UAV Eight-Capability Factor Pairwise Comparison.

	UAVSpeed	UAVAltit	UAVMaxDetecRange	TimeBwDetec	Endurance	RefuelTime	SlewRate	Aperture
UAVSpeed	1	1/3	1/4	3	1/5	2	1/2	1/6
UAVAltit	3	1	1/2	5	1/3	4	2	1/4
UAVMaxDetecRange	4	2	1	6	1/2	5	3	1/3
TimeBwDetec	1/3	1/5	1/6	1	1/7	1/2	1/4	1/8
Endurance	5	3	2	7	1	6	4	1/2
RefuelTime	1/2	1/4	1/5	2	1/6	1	1/3	1/7
SlewRate	2	1/2	1/3	4	1/4	3	1	1/5
Aperture	6	4	3	8	2	7	5	1

Normally, a user compares a single factor against other factors and assigns a score depending on how important it is (from one to nine, where one is equally preferred and nine is extremely preferred) (Bodin and Gass 2003). For this study, however, the factor's values for importance are informed by the regression analysis results in the data

correlation section. The Estimate column in the regression analysis shows how much change in the MOE can be caused by the one-unit change in the factor. For example, in the MOE 1 regression analysis, the UAV aperture factor has a greater effect on the percentage of detected red agents over UAV endurance, and hence, the UAV aperture is preferred over the UAV endurance factor and receives a higher value.

Data in Table 7 represent the importance value when comparing the row factor to the column factor. An integer (1 to 9) means the factor in the row is more preferred to the factor in the column by the integer amount. A fraction of the integer indicates that the factor in the row is less preferred than the factor in the column.

The next step is to normalize the data in the matrix shown in Table 7 to obtain the factors' weight scores. First, we sum each of the pairwise comparison columns; then, we divide each entry cell in the matrix by its column sum value (Bodin & Gass 2003). The average value in each row of the normalized matrix serves as the weight value for the UAV capability factor. Table 8 presents the score results, which are highlighted in orange.

Table 8. UAV Eight Factors' Weight Scores.

	Normalizing and Comparisons								
	UAV Speed	UAV Altit	UAV Max Detec Range	Time Bw Detec	Endur-ance	Refuel Time	Slew Rate	Aper-ture	Score
UAVSpeed	0.05	0.03	0.03	0.08	0.04	0.07	0.03	0.06	0.05
UAVAltit	0.14	0.09	0.07	0.14	0.07	0.14	0.12	0.09	0.11
UAVMaxDetecRange	0.18	0.18	0.13	0.17	0.11	0.18	0.19	0.12	0.16
TimeBwDetec	0.02	0.02	0.02	0.03	0.03	0.02	0.02	0.05	0.02
Endurance	0.23	0.27	0.27	0.19	0.22	0.21	0.25	0.18	0.23
RefuelTime	0.02	0.02	0.03	0.06	0.04	0.04	0.02	0.05	0.03
SlewRate	0.09	0.04	0.04	0.11	0.05	0.11	0.06	0.07	0.07
Aperture	0.27	0.35	0.40	0.22	0.44	0.25	0.31	0.37	0.33

Lawrence Bodin and Saul Gass explain the 10% rule, which refers to the consistency level that AHP users have to maintain. It reflects that users were consistent in the preference rating in the pairwise matrix. Our preference rating in Table 7 has resulted

in 4.1%, which is a satisfactory ratio of consistency (Bodin & Gass 2003). Refer to Appendix E for the full calculations.

b. Design Points Relative Cost Calculation

Table 9 illustrate the process the author used to calculate the relative cost for each design point. First, we break down the cost of one vehicle of the Raven RQ-11 UAV based on the calculated UAV capability weights in Table 8. The second row (cost per factor) shows the cost of each capability in regards to the relative weights of the factor. Next, we compare each Raven RQ-11 capability to the DP capability and compute the percentage difference. The resulting percentage is then multiplied by the Raven RQ-11 capability relative cost (cost per factor row) to calculate the required DP relative cost. Table 9 shows (DP 1) relative cost calculation, following this process, has resulted in a total relative cost for DP 1 equals $65,440.

There are some limitations to the relative cost calculation used in this study based on the assumptions made by the author. Each design point is an enhancement or a decrement from the reference Raven RQ-11 capabilities. The cost for the enhancement is proportional and linear to the importance of the characteristic. We alert the readers that this is an estimation for the DP cost and not a precise cost value.

Table 9. Design Point Relative Cost Calculation.

	UAV Speed	UAV Altit	UAV Max Detec	Time Bw Detec	Endur-ance	Refuel Time	Slew Rate	Aper-ture	Sum
$ 34,000.00	0.050	0.108	0.157	0.024	0.227	0.034	0.073	0.327	1
cost per factor	$1,693.06	$3,660.52	$5,333.03	$821.63	$7,729.54	$1,156.52	$2,495.72	$11,109.97	$34,000.00
Raven RQ-11 capability	80	3000	1000	20	1	60	60	60	
DP capability	166	3234	2078	10	2	53	299	89	
% Change	1.08	0.08	1.08	0.50	1.00	0.12	3.98	0.48	
% Change cost	$1,820.04	$ 285.52	$5,749.01	$410.82	$7,729.54	$ 134.93	$9,941.30	$ 5,369.82	$31,440.97
								cost 1 UAV	$65,440.97

The resulting relative cost for one UAV in Table 9 is multiplied by three (for a set of three UAVs) and then added to the cost of the two ground control stations and

supporting equipment. A similar methodology is used for all 260 DPs to calculate each DP's total relative cost to the system (see Appendix F).

c. Low Red Stealth Relative Cost Tradeoff

All MOEs' values for low red stealth DPs will be plotted against the total system relative cost. This can better illustrate the best DP that maximizes the MOE value for the lowest relative cost value in both case scenarios.

(1) MOE 1 vs. Relative Cost (Low Stealth)

Figure 23 presents each MOE 1 DP with its total system relative cost value. The dashed black line is the MOE #1 threshold. DPs in the red circle represent the DPs that achieve the threshold for both MOEs. The orange line represents the relative efficiency frontier line that connects the DPs with the highest MOE #1 value at their relative total cost value.

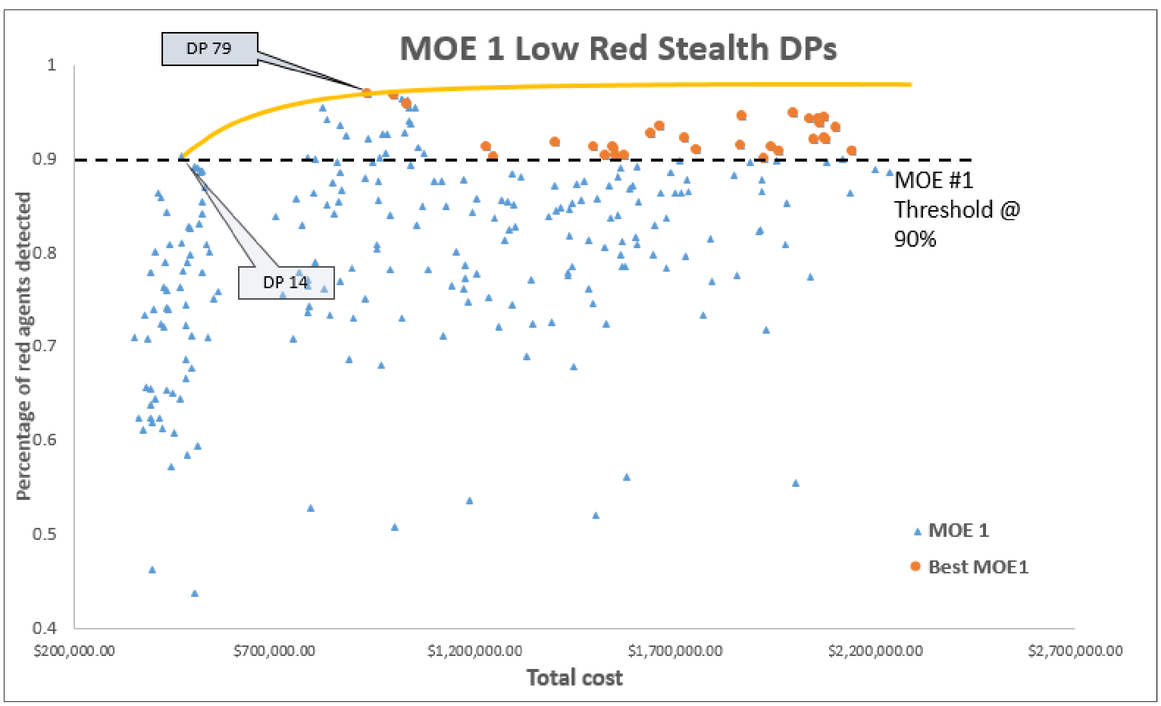


Figure 23. Relative Efficiency Frontier for MOE 1 (Low Red Stealth).

As shown in Figure 23, DP 79 meets both MOEs' thresholds with the lowest relative total system cost of $935,222. Other DPs meet both MOEs thresholds, but with a more expensive relative total system cost.

The cheapest option that reaches the threshold of MOE 1 only is DP 14 (90.35%). It has a relative total system cost that is almost half the DP 79 ($467,611.49), but DP 14's time to detect 40% of the red agents is higher than the MOE 2 threshold of 5.93 hours.

(2) MOE 2 vs. Relative Cost (Low Stealth)

Figure 24 presents each MOE 2 DP with its relative system cost. The dashed black line represents the MOE 2 threshold of 3.55 hours. Similarly, DPs in the red circle represent the DPs that achieve the threshold for both MOEs. The orange line represents the relative efficiency frontier line that connects the DPs with the lowest MOE #2 value.

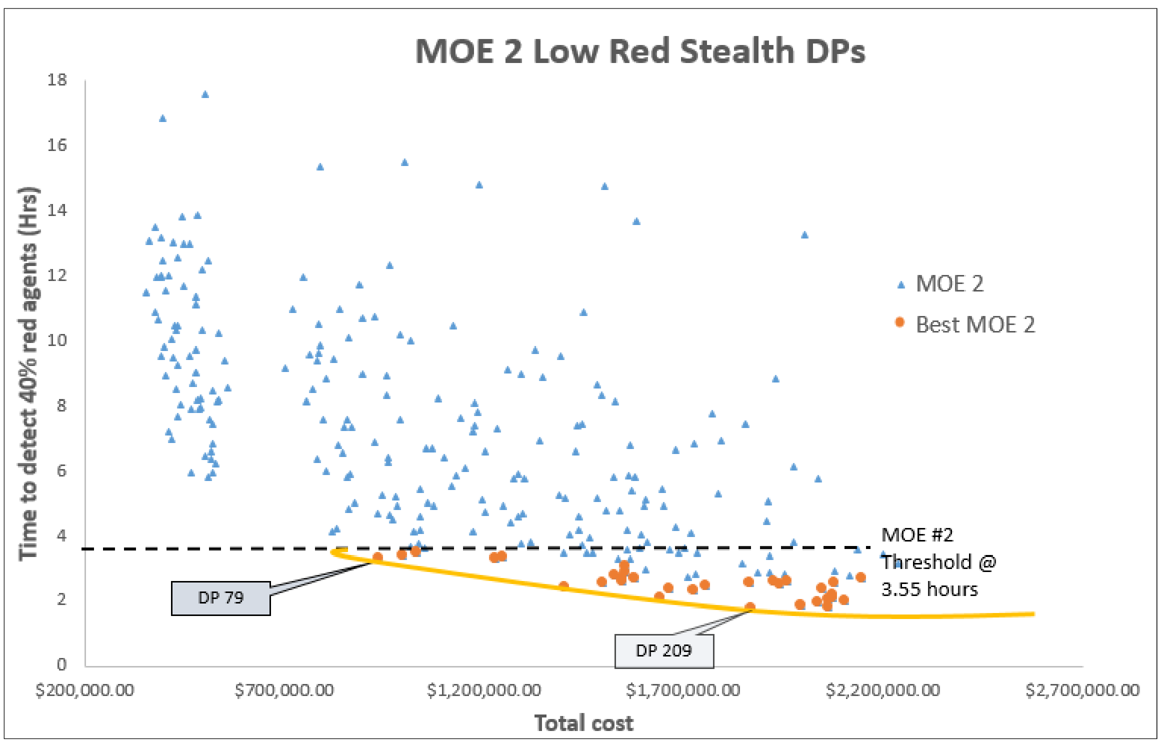


Figure 24. Relative Efficiency Frontier for MOE 2 (Low Red Stealth).

As shown in Figure 24, DP 79 has the lowest relative cost and satisfies both MOEs with an MOE 2 value of 3.28 hours. No other DP can reach the MOE 2 threshold at cheaper relative cost. Other DPs fall into the relative efficiency frontier curve and could deliver less time than DP 79, but they will relatively cost more. For example, DP 209 can expend the least time to detect 40% of the red agents (1.77 hours) but will have a relative cost of exactly double the price $1,870,445.94 as that of DP 79.

(3) Low Stealth Design Points Relative Cost

Table 10 presents the low red stealth design points with their relative cost. These relative costs serve only as a guide for the GCF because actual UAV component cost breakdowns were hard to obtain during the timeframe of this study. Actual costs would have to be considered for comparison if GCF needs to purchase a UAV with greater capability to fulfill its needs.

Table 10. Low Red Stealth DP Relative Cost.

DP	Num UAV	UAV Speed	UAV Altit	UAV Max Detec Range	Time Bw Detec	Endur-ance	Refuel Time	Slew Rate	Aper-ture	Red Stealth	MOE2 time To Detect 40% (Hr)	MOE1 %Red Agent Detected	**Relative Cost**
79	2	149	4641	3344	19	4	37	201	116	68	3.28	0.96895	$ 935,222.97
106	2	118	7844	3953	8	5	42	243	114	69	3.47	0.95805	$ 1,030,993.22
110	2	134	6906	3016	10	5	45	304	103	66	3.37	0.9676	$ 998,338.46
140	3	142	3078	3906	13	2	43	154	101	65	3.29	0.91215	$ 1,230,764.96
141	3	198	5578	3063	19	2	32	173	109	71	3.34	0.9016	$ 1,248,557.99
144	3	149	4641	3344	19	4	37	201	116	68	2.42	0.9175	$ 1,402,834.46
150	3	179	4016	2219	6	8	41	65	102	71	2.89	0.9027	$ 1,555,820.62
159	3	164	7688	2031	16	7	60	163	92	66	2.76	0.90325	$ 1,527,727.19
163	3	114	7766	2922	15	7	37	121	91	66	2.67	0.9112	$ 1,548,796.06
171	3	118	7844	3953	8	5	42	243	114	69	2.57	0.9117	$ 1,546,489.82
172	3	84	4563	2547	9	8	52	83	98	72	3.06	0.9008	$ 1,556,531.10
175	3	134	6906	3016	10	5	45	304	103	66	2.53	0.9127	$ 1,497,507.69
201	4	172	3938	2594	5	3	40	327	85	68	2.29	0.9216	$ 1,725,460.02
205	4	142	3078	3906	13	2	43	154	101	65	2.06	0.92695	$ 1,641,019.94
206	4	198	5578	3063	19	2	32	173	109	71	2.34	0.9341	$ 1,664,743.99
209	4	149	4641	3344	19	4	37	201	116	68	1.77	0.9449	$ 1,870,445.94
212	4	148	7297	1797	10	5	44	308	108	72	2.51	0.9126	$ 1,941,283.65
215	4	179	4016	2219	6	8	41	65	102	71	2.08	0.94435	$ 2,074,427.50
224	4	164	7688	2031	16	7	60	163	92	66	1.94	0.942	$ 2,036,969.58
228	4	114	7766	2922	15	7	37	121	91	66	2.04	0.93765	$ 2,065,061.41
229	4	86	4406	3672	14	6	53	196	75	71	2.61	0.90785	$ 1,962,672.06
233	4	136	3391	3297	13	7	40	318	68	67	2.54	0.92015	$ 2,078,105.80
236	4	118	7844	3953	8	5	42	243	114	69	1.81	0.94225	$ 2,061,986.43
237	4	84	4563	2547	9	8	52	83	98	72	2.15	0.92205	$ 2,075,374.80
240	4	134	6906	3016	10	5	45	304	103	66	1.84	0.9488	$ 1,996,676.91

Table 10 shows that DP 79 is the lowest relative cost option in addition to being the highest MOE 1 percentage of detection. Therefore, we can conclude that DP 79 will provide the best relative cost efficiency.

d. High Red Stealth Relative Cost Tradeoff

If GCF decided that it would go with the high red stealth scenario, different design point MOE values should be plotted against the relative total system cost. Figure 21 in the partition tree analysis section shows that seven possible DPs satisfy both MOEs

with a high red stealth value; only one of them, though, can achieve both MOEs with less than four UAV sets.

(1) MOE 1 vs. Relative Cost (High Stealth)

Similarly, Figure 25 represents each MOE 1 DP with its relative total system cost for the high red stealth case. DPs in red circles represent the seven DP options that can meet both MOEs for the high red stealth scenario. DP 176 meets both MOEs' thresholds with the lowest relative total system cost of $1,577,786 for the high red stealth scenario. DP 176 provides a 90.2% detection of the red agents, while DP 241 provides the highest possible percentage of red agent detection for the high red stealth DP option of 93.24%. This design point option requires an additional $525k, however, when compared to DP 176.

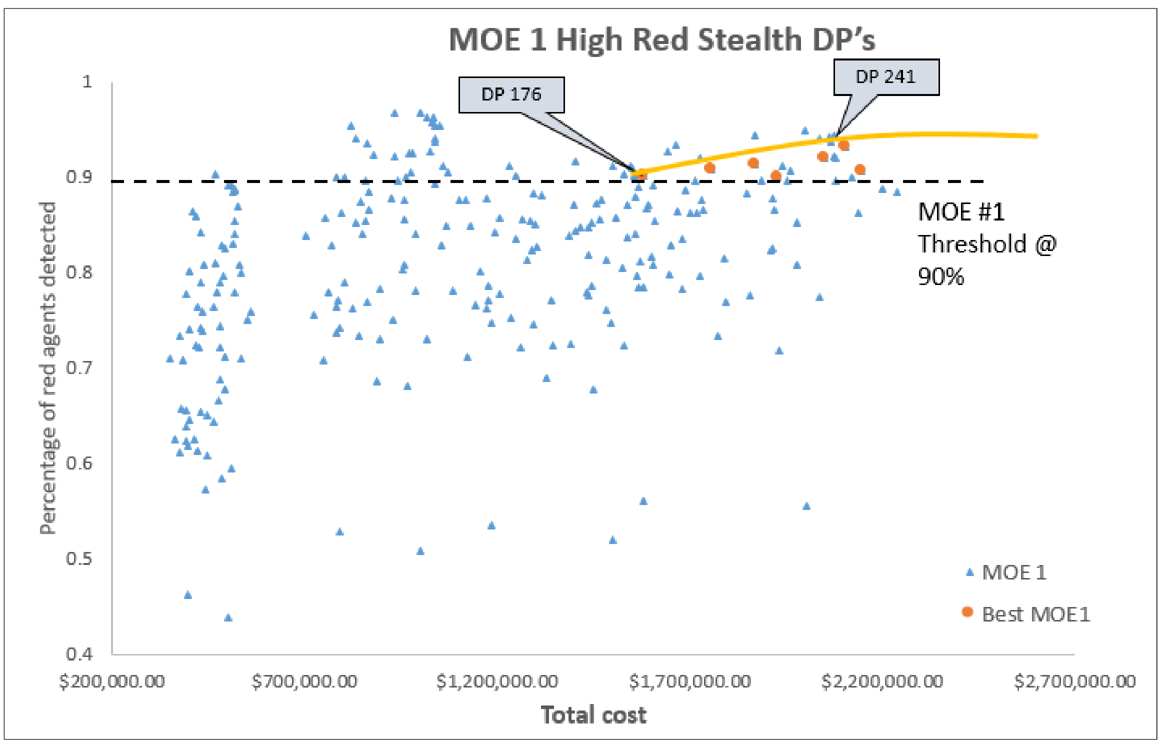


Figure 25. Relative Efficiency Frontier for MOE 1 (High Red Stealth).

(2) MOE 2 vs. Relative Cost (High Stealth)

Figure 26 represents the MOE 2 DP for high red stealth with a relative total system cost value. DP 176 has the least relative cost and satisfies both MOEs with an MOE 2 value of 2.69 hours. Nonetheless, DP 241 can satisfy both MOEs and provide a better MOE 2 value of 1.99 hours.

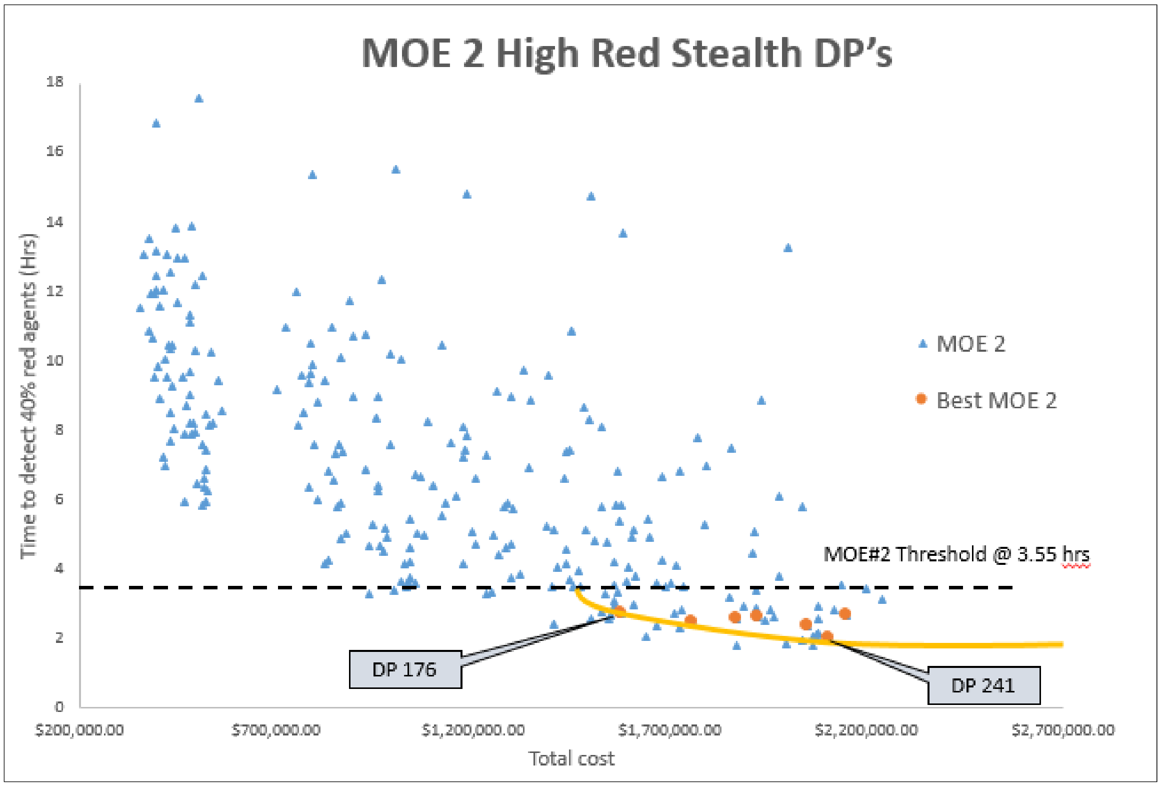


Figure 26. Relative Efficiency Frontier for MOE 2 (High Red Stealth).

(3) High Stealth Design Points Relative Cost

Table 11 represents all design points for the high red stealth scenario and its relative cost. DP 176 is the low relative cost option if the GCF decided to account for highly stealthy enemies. However, other design point options, such as DP 241 provide a higher percentage of detection and less time to detect 40% of the red agents when red stealth is high. Although it is relatively more expensive than DP 176, the added benefits of DP 241 may justify the cost.

Table 11. High Red Stealth DP Options Relative Cost.

DP	Num UAV	UAV Speed	UAV Altit	UAV Max Detec Range	Time Bw Detec	Endur-ance	Refuel Time	Slew Rate	Aper-ture	Red Stealth	MOE2 time To Detect 40% (Hr)	MOE1 %Red Agent Detected	**Relative Cost**
176	3	106	5266	2734	7	6	31	346	120	75	2.69	0.9028	***$ 1,577,786.87***
211	4	183	5188	2172	7	6	60	294	118	77	2.36	0.9207	***$ 2,049,055.26***
221	4	181	3469	3250	17	5	57	158	117	80	2.58	0.9004	***$ 1,925,269.63***
226	4	185	6281	3813	18	6	49	332	100	78	2.68	0.9072	***$ 2,146,678.15***
227	4	140	5500	2500	13	5	45	210	90	75	2.53	0.91465	***$ 1,867,307.31***
241	4	106	5266	2734	7	6	31	346	120	75	1.99	0.9324	***$ 2,103,715.83***
246	4	112	6047	2313	16	3	33	351	96	74	2.45	0.9093	***$ 1,755,737.39***

e. Design Points Mission Success Probability

MOE 1 and 2 data for each design point resulted from averaging 40 runs of this DP, as discussed in the section on the number of replications. For each design point that was successful in meeting the threshold of both MOEs, we ran the replication an additional 100 times. This allows calculating the proportion of those runs that effectively meet both MOEs' mission success (see Appendix G).

We calculated a 95% confidence interval of the proportion over the 100 results for each DP. The lower CI value defines the conservative estimate of a DP's probability of mission success.

In Figures 27 and 28, we plotted both scenarios' lower level of the 95% CI for the 100 runs. Figure 27 shows that the low red stealth DP 79 has a 97.04% probability of mission success. It also shows that there are multiple DP options that achieved a 100% probability of mission success. The cheapest DP for the low red stealth scenario that scores 100% is DP 205. Although it relatively costs $705,000 USD more than DP 79, it increases mission success by only 3%.

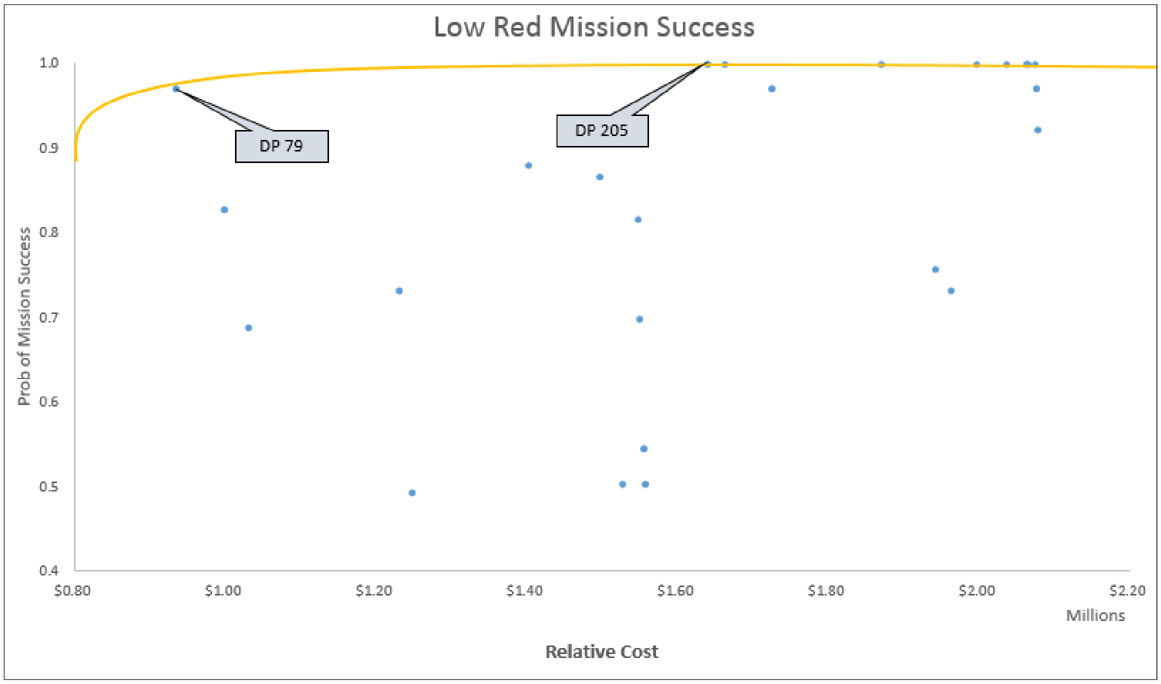


Figure 27. Low Red Stealth Mission Success.

The observation regarding the high red stealth DPs in Figure 28 shows that the most cost-effective option for high red stealth, DP 176, has a low probability of mission success, at only 44.18%. This indicates that if this option is chosen by the GCF, it has a low probability of delivering the required MOE thresholds. The other DP option for the high red stealth scenario is DP 241; this DP option will provide 100% probability of mission success.

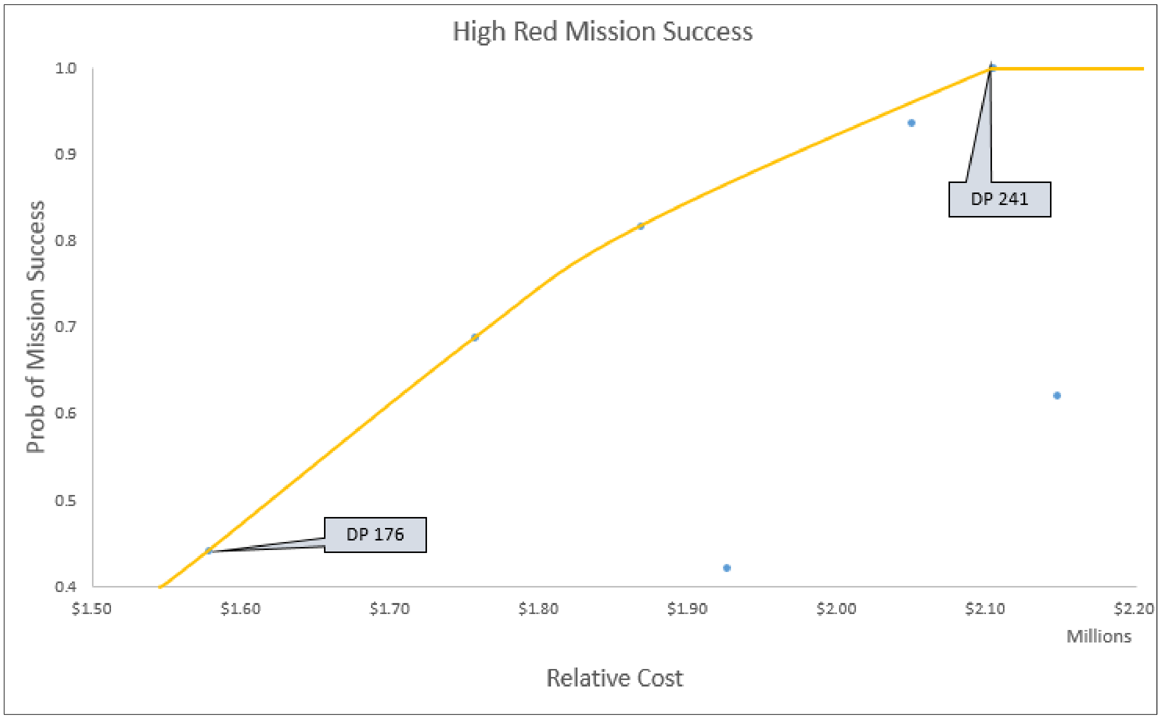


Figure 28. High Red Stealth Mission Success.

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V. CONCLUSION

This research examines how the addition of UAVs in the detection operation along the border of Yemen and Saudi Arabia can help improve the low detection rates of infiltrators. Findings from this study provide useful information for decision makers seeking suitable acquisition options for an appropriate UAV to support GCF ground forces in the detection operation.

To provide support for the GCF on how to defend their operational areas against enemy incursions and reconnaissance, we examined the role of UAV technology for the Decisive Storom operation sin Yemen. Using a systems engineering mindset and applying modeling and simulation, aided in providing insights to the detection capabilities that Gulf Coalition Force's desires. The experimental design helped determine the optimal technical characteristics for a UAV that can enhance the ISR role in the operation area. Regression and tree analysis tools were used for exploring and examining all design points in this study. Finally, the author conducted a comparative cost analysis to identify the desirable option GCF wish to pursue for both cases in this study. These outcomes can help the GCF decision makers with their acquisition of UAVs for the Decisive Storm operations in Yemen.

A. PRIMARY FINDINGS

- The current detection capability of the GCF is insufficient in terms of detection frequency and time of detection. This situation drives the GCF's need for enhanced detection methods to protect the border more efficiently.
- Introducing UAVs to support the GCF operation can boost the percentage of enemy detections that the GCF can achieve. Despite the number of UAV sets employed in the simulations described in this research, the addition of this technology made a 49% increase in the percentage of enemy detections over the baseline model configuration, which employed no UAVs. The time to detect infiltrators also showed promising results with the inclusion of UAVs in the detection operation simulations.
- The introduction of UAVs into the detection operation improved the enemy detection rate; however, the UAVs failed to satisfy the operational

thresholds of both MOEs because the vehicles did not have the right capabilities.

- To minimize financial obligations and maximize cost efficiency, it is essential that decision makers select the right UAV group for the operation, as well as the optimal quantity of UAV sets required for the mission.

- Higher capability UAVs will provide the required operational goals and might even exceed them, but this option can lead to a substantial financial investment and surplus flight performance and sensor capabilities.

- The relative cost analysis section of this research reveals the desirable design point option for both case scenarios. Both design points for high and low red stealth scenarios have flight performance capabilities that fall into the Group 3 UAV category as described by the U.S. Army UAS Road Map 2010–2035 (Army UAS CoE 2010).

- The referenced UAV for this study was from the Group 1 UAV category as described by the U.S. Army UAS Road Map 2010–2035 (Army UAS CoE 2010); however, the best design points show a need to procure a Group 3 UAV to perform the detection operation on the Saudi-Yemeni border.

B. OTHER IMPORTANT FINDINGS

- A number of possible DPs can meet the threshold levels for both MOEs in either red stealth capability environment.

- The regression analysis discovered the factors that have the most significant effect on the MOEs. For the percentage of red agents detected, it specified that the red stealth level, number of UAVs, UAV maximum detection range, aperture angle, and the UAV endurance all have an effect on MOE 1. Additionally, the red stealth level, number of UAVs, UAV maximum detection range, aperture angle, UAV endurance, and UAV speed have an effect on the time it takes to detect 40% of the red agents. The regression analysis also shows that the red stealth level is a major factor in the detection of red agents.

- The partition tree analysis helped to identify the most suitable UAV factors for achieving the operational goals of the GCF in both extreme cases (high and low red stealth environment). Both cases have been broken down and the number of UAVs is a major factor in detection for both cases. Few design points showed that fewer than four UAV sets are able to meet both MOEs operational goals.

- The partition tree analysis showed that solutions using more UAVs tend to give better results or more options to achieve the MOEs' threshold, but the marginal improvement after the third UAV set does not appear to justify the cost in the low red stealth case.

- The relative cost analysis discovered the desirable UAV factor combination for both case scenarios. Specifically, DP 79 was the desired option for the low red stealth scenario. It has the highest percentage of red agent detection and it has a high probability of mission success.

- The relative cost analysis also discovered the desirable UAV factor combination for the high red stealth scenario. Specifically, DP 241 was the best design point option with the highest percentage of red agent detection and lowest time to detect 40% of the red agents. It also had a 100% probability of mission success. The relative cost analysis proved helpful in identifying the DPs for the GCF in their detection mission.

- The best UAV factors combination for the low red stealth scenario is as follows: speed of 149 knots, 4641 meters in altitude, maximum detection range of 3344 meters, 19 second time between detections, endurance of 4 hours, 37 minutes of refuel time, slew rate of 201 degrees, and an aperture of 116 degrees.

- The best UAV factors combination for the high red stealth scenario is as follows: speed of 106 knots, 5266 meters in altitude, maximum detection range of 2734 meters, 7 second time between detections, endurance of 6 hours, 31 minutes of refuel time, slew rate of 346 degrees, and an aperture of 120 degrees.

C. FUTURE STUDIES

As mentioned earlier in this thesis, our analyses identified other issues such as route development and UAV sensor capabilities that merit more consideration but fell outside the scope of this research. The following are potential areas to explore in future studies:

- Use the exact same type and number of GCF detection equipment and their technical parameters for future simulations.

- Model the impact of the friendly forces in the operational area or civilians by adding classification factors into the UAV.

- Study the effect of false targets detections that sensors generate.

- Consider a detection method that red agents can use against UAVs and allow them to hide before they are detected or cause damage to UAV.
- Consider adding extra manned aircraft, such as F-16s, in the operational area to support detection missions, to simulate the communication and data exchange between UAVs and manned aircrafts.
- Apply data-link communication timings to simulate real life scenario between UAVs and the command centers.
- Allow UAV to change flying paths based on target locations.
- Use detailed data for the reference UAV for the cost analysis.

APPENDIX A. 65 DESIGN POINTS

	UAVSpeed	UAVAltitude	UAVMaxDetRng	UAVMaxTimeBtwDet	UAVEndurance	UAVRefuelTime	UAVSlewRate	UAVAperture	Red Stealth
1	166	3234	2078	10	2	53	299	89	84
2	194	6594	1328	11	3	38	224	105	79
3	187	4797	3859	8	3	56	107	87	73
4	157	7453	3156	12	1	43	140	76	68
5	191	5344	1563	5	2	35	135	97	77
6	144	7609	1703	12	2	50	102	112	83
7	172	3938	2594	5	3	40	327	85	68
8	178	6828	3766	10	4	58	271	61	70
9	163	3156	1047	17	4	48	177	66	81
10	196	6438	2453	16	1	38	337	83	78
11	142	3078	3906	13	2	43	154	101	65
12	198	5578	3063	19	2	32	173	109	71
13	146	4094	1984	15	4	45	116	77	84
14	174	5734	2266	18	3	59	74	60	75
15	149	4641	3344	19	4	37	201	116	68
16	161	5891	2641	16	2	59	360	94	74
17	183	5188	2172	7	6	60	294	118	77
18	148	7297	1797	10	5	44	308	108	72
19	168	4953	2688	9	6	57	69	84	76
20	153	6672	3578	6	5	35	191	70	81
21	179	4016	2219	6	8	41	65	102	71
22	176	7141	1000	7	5	51	205	113	68
23	200	5031	3391	9	8	34	276	68	76
24	151	8000	3484	11	6	46	233	73	85
25	155	4250	1281	14	7	52	341	69	67
26	170	6125	1469	20	6	36	252	82	73
27	181	3469	3250	17	5	57	158	117	80
28	189	7219	2875	17	7	39	98	99	80
29	193	4484	1375	14	5	36	182	65	69
30	164	7688	2031	16	7	60	163	92	66
31	159	3625	3109	13	8	42	290	106	83
32	185	6281	3813	18	6	49	332	100	78
33	140	5500	2500	13	5	45	210	90	75
34	114	7766	2922	15	7	37	121	91	66

35	86	4406	3672	14	6	53	196	75	71
36	93	6203	1141	17	6	34	313	93	77
37	123	3547	1844	13	8	47	280	104	83
38	89	5656	3438	20	7	55	285	83	73
39	136	3391	3297	13	7	40	318	68	67
40	108	7063	2406	20	6	50	93	95	82
41	103	4172	1234	15	5	32	149	119	80
42	118	7844	3953	8	5	42	243	114	69
43	84	4563	2547	9	8	52	83	98	72
44	138	7922	1094	12	7	47	266	79	85
45	82	5422	1938	6	7	58	248	71	79
46	134	6906	3016	10	5	45	304	103	66
47	106	5266	2734	7	6	31	346	120	75
48	131	6359	1656	6	5	53	219	64	82
49	119	5109	2359	9	7	31	60	86	76
50	97	5813	2828	18	3	30	126	62	73
51	133	3703	3203	15	4	46	112	72	78
52	112	6047	2313	16	3	33	351	96	74
53	127	4328	1422	19	4	55	229	110	69
54	101	6984	2781	19	1	49	355	78	79
55	104	3859	4000	18	4	39	215	67	82
56	80	5969	1609	16	1	56	144	113	74
57	129	3000	1516	14	3	44	187	107	65
58	125	6750	3719	11	2	38	79	111	83
59	110	4875	3531	5	3	54	168	98	78
60	99	7531	1750	8	4	33	262	63	70
61	91	3781	2125	8	2	51	323	81	70
62	88	6516	3625	11	4	54	238	115	81
63	116	3313	2969	9	2	30	257	88	84
64	121	7375	1891	12	1	48	130	74	67
65	95	4719	1188	7	3	41	88	80	72

See text for data collection methods and details.

APPENDIX B. REQUIRED RUN CALCULATION

A. MOE 1

Calculate sample size required for desired CI precision		
alpha	0.05	Type I error rate
confidence	0.95	= 1 - alpha
z-sub-alpha-over-2	1.959963985	(assuming 2-tailed CI)
s (sample std dev)	8.769529432	
	Desired Width of CI (twice the Margin of Error)	6
	required sample size (n)	33

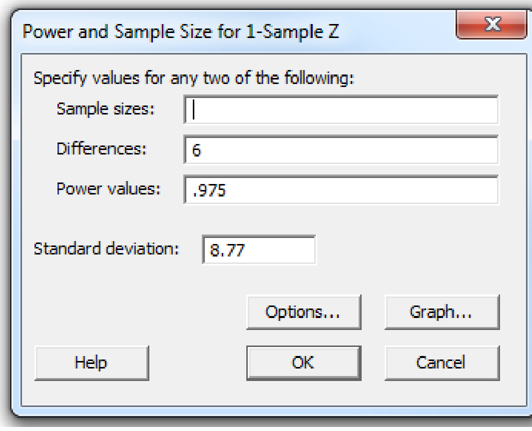
```
            Sample  Target
Difference    Size   Power  Actual Power
         6       8    0.47      0.490119
```

Power and Sample Size

```
1-Sample Z Test

Testing mean = null (versus not = null)
Calculating power for mean = null + difference
Alpha = 0.05  Assumed standard deviation = 8.77


            Sample  Target
Difference    Size   Power  Actual Power
         6      33   0.975      0.975591
```



B. MOE 2

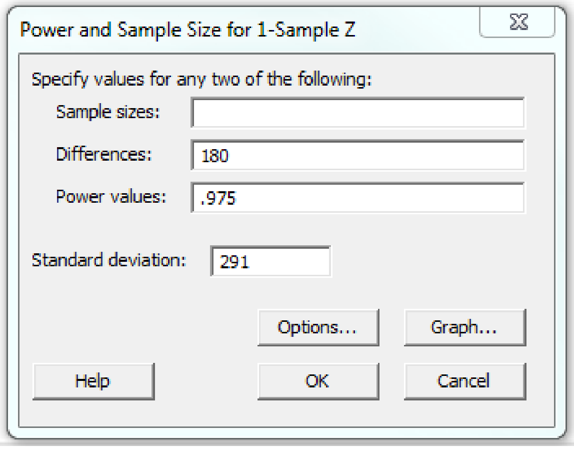
Method 2: Calculate sample size required for desired CI precision		
alpha	0.05	Type I error rate
confidence	0.95	= 1 - alpha
z-sub-alpha-over-2	1.959963985	(assuming 2-tailed CI)
s (sample std dev)	291	
	Desired Width of CI (twice the Margin of Error)	180
	required sample size (n)	41

Power and Sample Size

```
1-Sample Z Test

Testing mean = null (versus not = null)
Calculating power for mean = null + difference
Alpha = 0.05  Assumed standard deviation = 291


            Sample  Target
Difference    Size   Power  Actual Power
       180      41   0.975      0.977289
```



See text for data collection methods and details.

APPENDIX C. BLUE RADAR DESIGN POINTS AND DETECTION PROBABILITIES

DP	Num Radar	Range	Tme b/w Detection	Std Dev (Alleg2Cas.Red.)	Mean (PercentageRedDetected)
1	7	7313	60	8.625543461	0.4498
2	8	6875	67	7.571496821	0.41885
3	7	7750	81	9.532367263	0.41365
4	7	6500	69	8.320348859	0.4089
5	8	5875	71	9.23691035	0.3795
6	8	7375	98	8.80617499	0.3774
7	8	6750	89	9.884947116	0.37415
8	7	6188	85	8.621343521	0.36665
9	7	7563	103	8.689479345	0.36135
10	7	6313	93	8.859443752	0.3537
11	7	5750	83	8.208813275	0.348
12	8	5188	68	7.361542481	0.3375
13	8	6063	101	8.230493645	0.3349
14	7	7063	115	9.272201354	0.33405
15	8	6625	116	8.738215508	0.3301
16	7	5000	66	9.185237599	0.32825
17	7	5563	94	7.445141248	0.31965
18	8	5625	108	8.619447302	0.3035
19	8	5438	117	8.556898552	0.2872
20	7	4813	84	8.318615208	0.28615
21	7	4125	61	9.106070109	0.2849
22	7	4750	92	9.448884075	0.28095
23	7	4188	82	9.508397099	0.25945
24	7	4500	102	8.476059801	0.2471
25	7	4375	105	8.229052661	0.23995
26	6	7938	62	6.842364264	0.2331
27	6	7688	74	6.93814244	0.20925
28	5	7625	75	6.944422222	0.20665
29	6	7438	76	6.535112264	0.2052
30	5	7500	78	7.397851386	0.2026
31	6	6688	73	6.60414594	0.19755
32	5	7813	98	7.08008221	0.18805
33	5	7250	88	7.727365624	0.18585
34	5	5375	64	6.455170855	0.1857
35	6	8000	110	7.259829764	0.1825
36	5	7188	96	6.208141883	0.1787
37	5	6438	86	7.298752967	0.1768
38	6	6000	90	5.917759018	0.17365

39	6	7125	100	6.341560109	0.1736
40	6	5063	68	6.795737729	0.1717
41	5	7875	119	5.648689433	0.1714
42	5	5688	87	4.790749634	0.1713
43	5	4938	65	4.635357425	0.17095
44	5	6250	97	6.299725269	0.16835
45	6	6938	112	5.461050899	0.1647
46	5	5813	95	6.002349967	0.1633
47	6	7000	114	5.457939406	0.16085
48	6	4875	80	6.29183435	0.1601
49	4	6563	63	4.228641656	0.15725
50	5	4438	77	5.679246971	0.1549
51	6	4000	70	6.13418333	0.1525
52	4	6375	72	5.355981559	0.15135
53	5	5500	111	6.339487563	0.15125
54	6	5313	107	6.129740447	0.14875
55	6	4563	104	5.775223383	0.14135
56	6	4313	106	4.955636522	0.13715
57	5	4250	99	4.965973967	0.13685
58	4	5938	79	4.711143364	0.1368
59	5	4688	120	5.496852246	0.1304
60	4	6813	113	5.323147324	0.1277
61	6	4063	118	5.005381719	0.1253
62	4	6125	109	4.933142755	0.1237
63	4	5250	91	4.091814844	0.12155
64	4	4625	83	4.327535569	0.11425
65	4	5125	113	4.291837811	0.10825

See text for data collection methods and details.

APPENDIX D. DETAILED PARTITION TREE ANALYSIS

A. PARTITION TREE ANALYSIS FOR DESIGN POINTS ACHIEVED BOTH MOE'S

The partition tree in Figure 29 shows up to three splits of each MOE's options using Red Stealth as the first split factor. The Red Stealth factor is a non-controllable factor, and it depends on how well the red agents hide from detection. Splitting the tree according to the Red Stealth factor as a first split will assist the GCF in determining the ideal UAV in both extreme cases for detecting red agents at their most detectable (best case) and least detectable (worst case). We will further split the tree to see how the UAV factors contribute to success in the highest and lowest levels of detectability cases.

The top box in Figure 29 shows a count of 32 DPs in the Red/Blue bar out of a total of 260 DPs. This means that 32 DPs accomplished the requirement for both MOEs' threshold by detecting 90% of the red agents within 3.55 hours. Blue means "YES" and red means "NO."

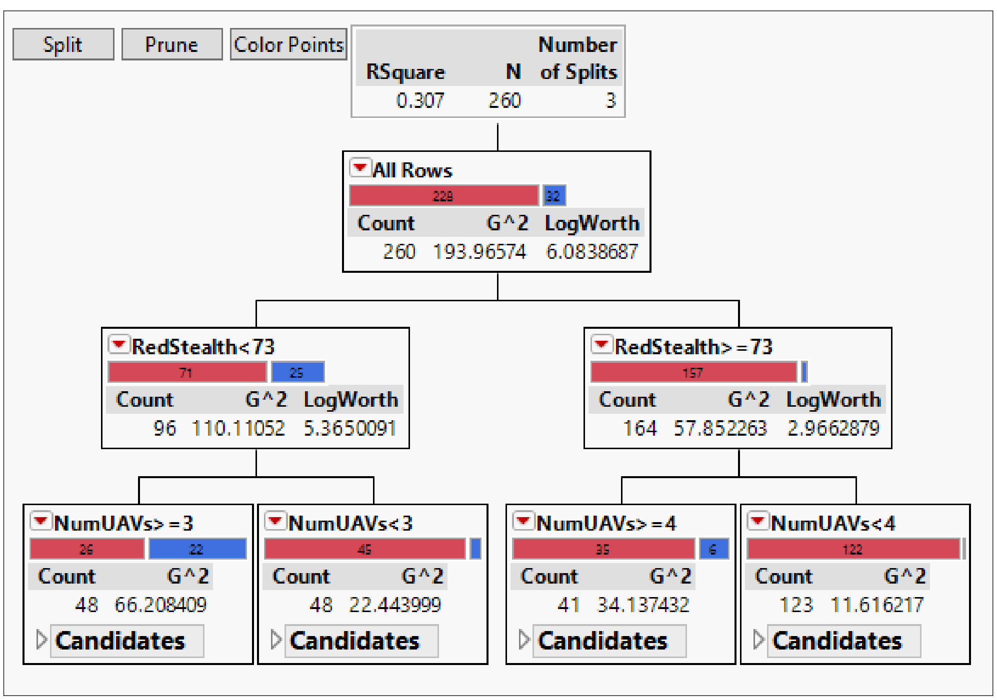


Figure 29. Partition Tree for DPs Achieved Both MOEs.

Splitting the 260 design points using the Red Stealth factor resulted in 96 DPs (top left box) having a red stealth value of less than 73 (Red Stealth<73) among all 260 DPs. Twenty-five of those DPs only can achieve the detection of 90% of the red agents in less than 3.55 hours, while 71 of the DPs failed. On the other side (top right box), 164 DPs (top right box) have a red stealth value of higher than or equal to 73 (Red Stealth>=73) out of 260 DPs. Only seven DPs can achieve the detection of 90% of the red agents in less than or equal to 3.55 hours, while 157 could not.

Further analysis will be broken down based on best and worst case red agent concealment scenarios.

B. LOW RED STEALTH SCENARIO

The second split after the Red Stealth factor is how many sets of UAVs can satisfy the required criteria for both MOEs. The left side box in Figure 30 represents a possible 48 DP options among the 260 DPs that have three sets or more than three sets of UAVs. There are 22 DPs in that box that can achieve both MOEs. A third split in same figure under the Red Stealth factor is when the UAV sensor can detect a maximum range of more than or equal to 1797 meters; 22 DPs out of 32 DPs are possible options. Finally, a fourth split is to check whether the aperture angle width is greater than or equal to 91 degrees. Nineteen DPs are in the blue area, which means 19 DPs can achieve the best case MOE 1 and 2 thresholds if the UAV aperture angle width is greater than or equal to 91 degrees and the sensor maximum detection range is greater than 1797 meters.

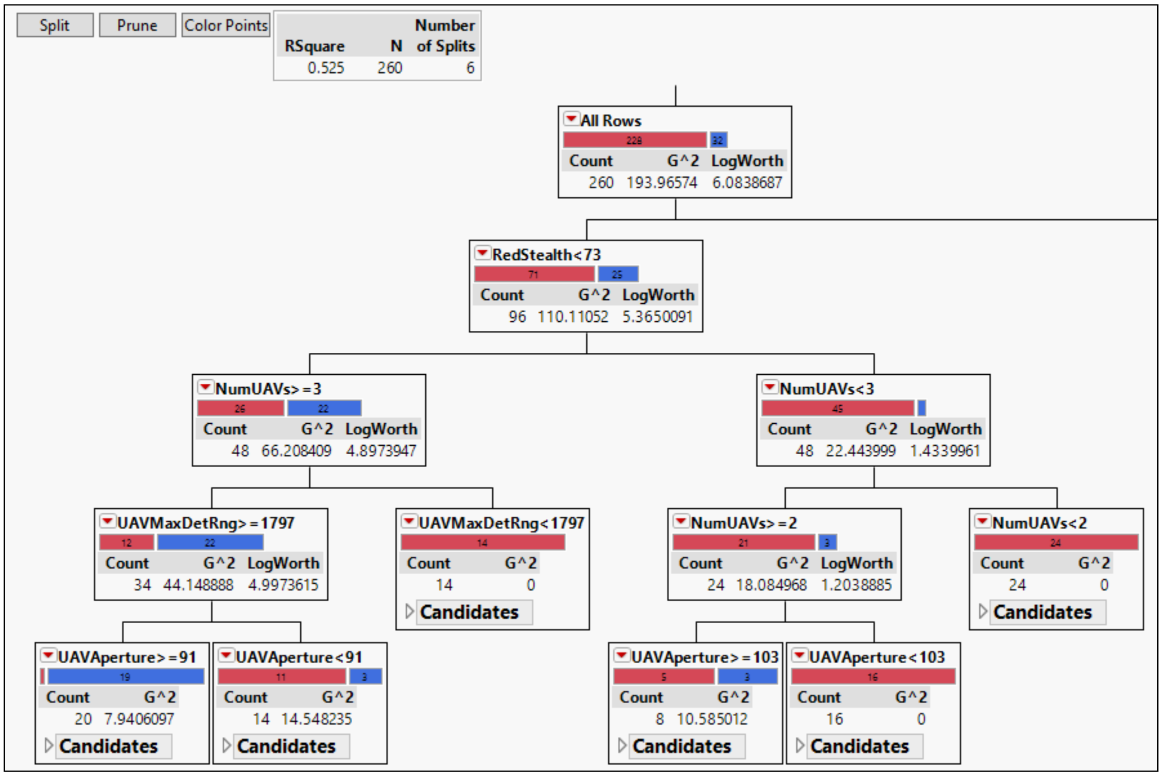


Figure 30. Low Red Stealth Partition Tree.

There is another path to success with fewer UAV sets if the GCF decided to go for a low number of UAVs solution. Looking at the right side portion of the second split will determine what capabilities are required to achieve the best MOE 1 and 2 criteria. The right side shows that with fewer than three UAVs, there are three DPs than can achieve the best MOE 1 and 2, while 45 out of the 48 DPs could not.

If the fewer than three UAV sets path was selected, a third split shows three DPs out of 24 in the blue area, which means that there should be at least two or more UAV sets to satisfy the best case MOE's criteria; fewer than two UAVs is not a possible option. Further splitting shows that UAV aperture is required to be greater than or equal to 103 degrees for fewer than two UAVs to satisfy the best case MOEs. Three DPs are in the blue area if the aperture is greater than 103 degrees.

C. HIGH RED STEALTH SCENARIO

Figure 31 shows having a red stealth value of at least 73 resulted in 164 DPs among all 260 DPs. Only seven DPs met the criteria of being capable of detecting 90% of the red agents in 3.55 hours or less. This shows the higher the red stealth value, the harder it is to detect red agents or the fewer options we have to be able to detect them.

The second split is how many UAV sets can satisfy the required criteria for both MOEs. The box on the left side presents a possible 41 DP options among the 260 DPs that have at least four sets of UAVs. There are six DPs in that box in blue, which means that those DPs are possible options to achieve both MOEs' criteria.

A third split under the Red Stealth factor is to check whether the aperture angle width is at least 90 degrees; the same six DPs from the earlier split are the only options. Anything with less than a 90-degree aperture is not an option. Finally, a fourth split occurs when the UAV sensor can detect a maximum range of at least 2172 meters. Again, the same six DPs fall into this UAV capability and anything less than 2172 meters sensor detection is not an option. This means the MOE 1 and MOE 2 threshold is achievable when red stealth is high if at least four UAV sets are used, sensor maximum detection range is at least 2172 meters, and the aperture angle width is at least 90 degrees.

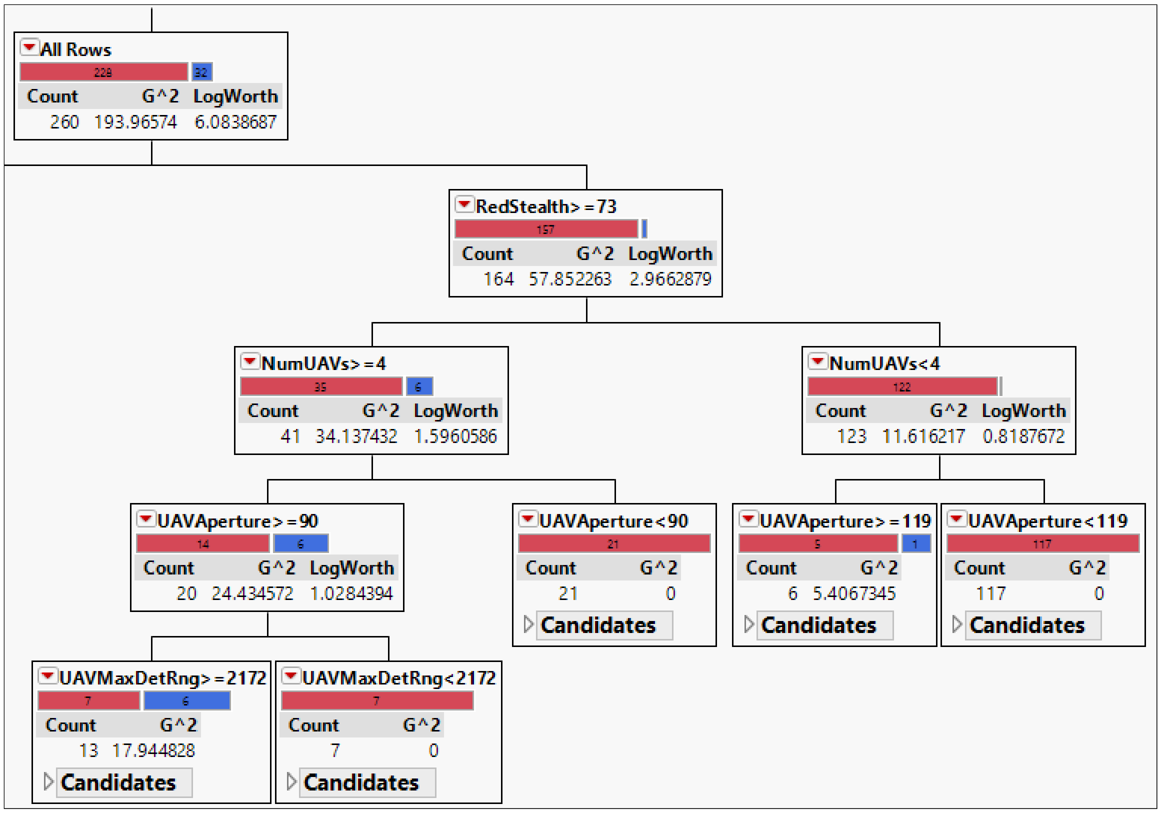


Figure 31. High Red Stealth Partition Tree

If there is a requirement to reduce the number of UAV sets, while using high value for red stealth, only one possible DP option can achieve the MOE 1 and MOE 2 threshold. The box on the right shows a total of 123 DPs available for fewer than four UAVs among the 260 DPs; only one is in the blue area. Further splitting this box to explore what is the single option that can satisfy the requirement yields a sensor capability having an aperture of at least 119 degrees. Only one DP out of five in this box falls into the blue area.

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APPENDIX E. ANALYTIC HIERARCHY PROCESS

A. PAIRWISE COMPARISON AND COLUMN SUM

	UAVSpeed	UAVAltit	UAVMaxDetecRange	TimeBwDetec	Endurance	RefuelTime	SlewRate	Aperture
UAVSpeed	1	1/3	1/4	3	1/5	2	1/2	1/6
UAVAltit	3	1	1/2	5	1/3	4	2	1/4
UAVMaxDetecRange	4	2	1	6	1/2	5	3	1/3
TimeBwDetec	1/3	1/5	1/6	1	1/7	1/2	1/4	1/8
Endurance	5	3	2	7	1	6	4	1/2
RefuelTime	1/2	1/4	1/5	2	1/6	1	1/3	1/7
SlewRate	2	1/2	1/3	4	1/4	3	1	1/5
Aperture	6	4	3	8	2	7	5	1
column sum	21.833333	11.28333	7.45	36	4.5928571	28.5	16.08333	2.717857

B. NORMALIZATION

	UAVSpeed	UAVAltit	UAVMaxDetecRange	TimeBwDetec	Endurance	RefulTime	SlewRate	Aperture
UAVSpeed	0.0458015	0.029542	0.033557047	0.083333333	0.0435459	0.07017544	0.031088	0.061323
UAVAltit	0.1374046	0.088626	0.067114094	0.138888889	0.0725765	0.14035088	0.124352	0.091984
UAVMaxDetecRange	0.1832061	0.177253	0.134228188	0.166666667	0.1088647	0.1754386	0.186528	0.122646
TimeBwDetec	0.0152672	0.017725	0.022371365	0.027777778	0.0311042	0.01754386	0.015544	0.045992
Endurance	0.2290076	0.265879	0.268456376	0.194444444	0.2177294	0.21052632	0.248705	0.183968
RefulTime	0.0229008	0.022157	0.026845638	0.055555556	0.0362882	0.03508772	0.020725	0.052562
SlewRate	0.0916031	0.044313	0.044742729	0.111111111	0.0544323	0.10526316	0.062176	0.073587
Aperture	0.2748092	0.354505	0.402684564	0.222222222	0.4354588	0.24561404	0.310881	0.367937

C. SCORES AND CONSISTENCY

	UAVSpee	UAVAltit	UAVMaxD	TimeBwDe	Endurance	RefulTime	SlewRate	Aperture	Score	consistency
UAVSpeed	0.0458	0.029542	0.033557	0.0833333	0.0435459	0.070175	0.031088	0.061323	0.04979578	8.074073637
UAVAltit	0.1374	0.088626	0.067114	0.1388889	0.0725765	0.140351	0.124352	0.091984	0.10766222	8.328310151
UAVMaxDetecRange	0.18321	0.177253	0.134228	0.1666667	0.1088647	0.175439	0.186528	0.122646	0.15685387	8.474347312
TimeBwDetec	0.01527	0.017725	0.022371	0.0277778	0.0311042	0.017544	0.015544	0.045992	0.02416572	8.157015878
Endurance	0.22901	0.265879	0.268456	0.1944444	0.2177294	0.210526	0.248705	0.183968	0.22733952	8.547836835
RefulTime	0.0229	0.022157	0.026846	0.0555556	0.0362882	0.035088	0.020725	0.052562	0.03401529	8.07193913
SlewRate	0.0916	0.044313	0.044743	0.1111111	0.0544323	0.105263	0.062176	0.073587	0.07340364	8.174082069
Aperture	0.27481	0.354505	0.402685	0.2222222	0.4354588	0.245614	0.310881	0.367937	0.32676396	8.507300303
								CI	0.04169474	
								CR	0.02957074	

See text for data collection methods and details.

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APPENDIX F. TOTAL SYSTEM RELATIVE COST CALCULATION

		1 UAV set Cost				Total system relative cost
DP	No# of UAVs	1 UAV cost	3 UAV cost	2 GCS + Supp Equip	cost	
0	1	$ 65,440.97	$ 196,322.92	$ 198,000.00	$ 394,322.92	$ 394,322.92
1	1	$ 73,954.14	$ 221,862.43	$ 198,000.00	$ 419,862.43	$ 419,862.43
2	1	$ 76,687.89	$ 230,063.67	$ 198,000.00	$ 428,063.67	$ 428,063.67
3	1	$ 59,507.63	$ 178,522.90	$ 198,000.00	$ 376,522.90	$ 376,522.90
4	1	$ 61,010.15	$ 183,030.46	$ 198,000.00	$ 381,030.46	$ 381,030.46
5	1	$ 64,353.94	$ 193,061.82	$ 198,000.00	$ 391,061.82	$ 391,061.82
6	1	$ 77,788.33	$ 233,365.00	$ 198,000.00	$ 431,365.00	$ 431,365.00
7	1	$ 88,095.77	$ 264,287.31	$ 198,000.00	$ 462,287.31	$ 462,287.31
8	1	$ 65,718.38	$ 197,155.15	$ 198,000.00	$ 395,155.15	$ 395,155.15
9	1	$ 64,767.91	$ 194,303.73	$ 198,000.00	$ 392,303.73	$ 392,303.73
10	1	$ 70,751.66	$ 212,254.99	$ 198,000.00	$ 410,254.99	$ 410,254.99
11	1	$ 72,728.67	$ 218,186.00	$ 198,000.00	$ 416,186.00	$ 416,186.00
12	1	$ 71,139.68	$ 213,419.04	$ 198,000.00	$ 411,419.04	$ 411,419.04
13	1	$ 62,219.77	$ 186,659.31	$ 198,000.00	$ 384,659.31	$ 384,659.31
14	1	$ 89,870.50	$ 269,611.49	$ 198,000.00	$ 467,611.49	$ 467,611.49
15	1	$ 74,680.66	$ 224,041.97	$ 198,000.00	$ 422,041.97	$ 422,041.97
16	1	$ 104,754.60	$ 314,263.81	$ 198,000.00	$ 512,263.81	$ 512,263.81
17	1	$ 95,773.64	$ 287,320.91	$ 198,000.00	$ 485,320.91	$ 485,320.91
18	1	$ 91,223.31	$ 273,669.92	$ 198,000.00	$ 471,669.92	$ 471,669.92
19	1	$ 93,049.80	$ 279,149.41	$ 198,000.00	$ 477,149.41	$ 477,149.41
20	1	$ 106,868.96	$ 320,606.87	$ 198,000.00	$ 518,606.87	$ 518,606.87
21	1	$ 88,555.26	$ 265,665.77	$ 198,000.00	$ 463,665.77	$ 463,665.77
22	1	$ 117,294.83	$ 351,884.49	$ 198,000.00	$ 549,884.49	$ 549,884.49
23	1	$ 103,741.17	$ 311,223.51	$ 198,000.00	$ 509,223.51	$ 509,223.51
24	1	$ 98,743.79	$ 296,231.38	$ 198,000.00	$ 494,231.38	$ 494,231.38
25	1	$ 93,389.22	$ 280,167.65	$ 198,000.00	$ 478,167.65	$ 478,167.65
26	1	$ 94,439.14	$ 283,317.41	$ 198,000.00	$ 481,317.41	$ 481,317.41
27	1	$ 107,161.53	$ 321,484.58	$ 198,000.00	$ 519,484.58	$ 519,484.58
28	1	$ 77,829.81	$ 233,489.42	$ 198,000.00	$ 431,489.42	$ 431,489.42
29	1	$ 103,747.47	$ 311,242.40	$ 198,000.00	$ 509,242.40	$ 509,242.40
30	1	$ 120,507.79	$ 361,523.36	$ 198,000.00	$ 559,523.36	$ 559,523.36
31	1	$ 112,889.85	$ 338,669.54	$ 198,000.00	$ 536,669.54	$ 536,669.54
32	1	$ 89,608.94	$ 268,826.83	$ 198,000.00	$ 466,826.83	$ 466,826.83
33	1	$ 106,088.45	$ 318,265.35	$ 198,000.00	$ 516,265.35	$ 516,265.35

34	1	$ 97,556.00	$ 292,668.01	$ 198,000.00	$ 490,668.01	$ 490,668.01
35	1	$ 94,841.53	$ 284,524.60	$ 198,000.00	$ 482,524.60	$ 482,524.60
36	1	$ 112,021.79	$ 336,065.37	$ 198,000.00	$ 534,065.37	$ 534,065.37
37	1	$ 110,524.60	$ 331,573.81	$ 198,000.00	$ 529,573.81	$ 529,573.81
38	1	$ 107,175.48	$ 321,526.45	$ 198,000.00	$ 519,526.45	$ 519,526.45
39	1	$ 93,742.31	$ 281,226.93	$ 198,000.00	$ 479,226.93	$ 479,226.93
40	1	$ 83,454.82	$ 250,364.45	$ 198,000.00	$ 448,364.45	$ 448,364.45
41	1	$ 105,832.20	$ 317,496.61	$ 198,000.00	$ 515,496.61	$ 515,496.61
42	1	$ 106,947.90	$ 320,843.70	$ 198,000.00	$ 518,843.70	$ 518,843.70
43	1	$ 100,777.76	$ 302,333.29	$ 198,000.00	$ 500,333.29	$ 500,333.29
44	1	$ 98,847.69	$ 296,543.06	$ 198,000.00	$ 494,543.06	$ 494,543.06
45	1	$ 100,389.74	$ 301,169.23	$ 198,000.00	$ 499,169.23	$ 499,169.23
46	1	$ 109,309.65	$ 327,928.96	$ 198,000.00	$ 525,928.96	$ 525,928.96
47	1	$ 81,658.93	$ 244,976.79	$ 198,000.00	$ 442,976.79	$ 442,976.79
48	1	$ 96,848.77	$ 290,546.30	$ 198,000.00	$ 488,546.30	$ 488,546.30
49	1	$ 66,776.04	$ 200,328.12	$ 198,000.00	$ 398,328.12	$ 398,328.12
50	1	$ 75,776.95	$ 227,330.85	$ 198,000.00	$ 425,330.85	$ 425,330.85
51	1	$ 80,311.45	$ 240,934.35	$ 198,000.00	$ 438,934.35	$ 438,934.35
52	1	$ 78,479.62	$ 235,438.86	$ 198,000.00	$ 433,438.86	$ 433,438.86
53	1	$ 64,660.47	$ 193,981.40	$ 198,000.00	$ 391,981.40	$ 391,981.40
54	1	$ 82,974.17	$ 248,922.50	$ 198,000.00	$ 446,922.50	$ 446,922.50
55	1	$ 54,419.76	$ 163,259.28	$ 198,000.00	$ 361,259.28	$ 361,259.28
56	1	$ 67,788.25	$ 203,364.76	$ 198,000.00	$ 401,364.76	$ 401,364.76
57	1	$ 72,785.63	$ 218,356.89	$ 198,000.00	$ 416,356.89	$ 416,356.89
58	1	$ 78,140.21	$ 234,420.62	$ 198,000.00	$ 432,420.62	$ 432,420.62
59	1	$ 77,090.29	$ 231,270.86	$ 198,000.00	$ 429,270.86	$ 429,270.86
60	1	$ 64,409.49	$ 193,228.48	$ 198,000.00	$ 391,228.48	$ 391,228.48
61	1	$ 93,720.78	$ 281,162.34	$ 198,000.00	$ 479,162.34	$ 479,162.34
62	1	$ 67,783.18	$ 203,349.54	$ 198,000.00	$ 401,349.54	$ 401,349.54
63	1	$ 51,021.64	$ 153,064.91	$ 198,000.00	$ 351,064.91	$ 351,064.91
64	1	$ 58,644.91	$ 175,934.73	$ 198,000.00	$ 373,934.73	$ 373,934.73
65	2	$ 65,440.97	$ 196,322.92	$ 198,000.00	$ 394,322.92	$ 788,645.84
66	2	$ 73,954.14	$ 221,862.43	$ 198,000.00	$ 419,862.43	$ 839,724.86
67	2	$ 76,687.89	$ 230,063.67	$ 198,000.00	$ 428,063.67	$ 856,127.35
68	2	$ 59,507.63	$ 178,522.90	$ 198,000.00	$ 376,522.90	$ 753,045.80
69	2	$ 61,010.15	$ 183,030.46	$ 198,000.00	$ 381,030.46	$ 762,060.92
70	2	$ 64,353.94	$ 193,061.82	$ 198,000.00	$ 391,061.82	$ 782,123.64
71	2	$ 77,788.33	$ 233,365.00	$ 198,000.00	$ 431,365.00	$ 862,730.01
72	2	$ 88,095.77	$ 264,287.31	$ 198,000.00	$ 462,287.31	$ 924,574.63
73	2	$ 65,718.38	$ 197,155.15	$ 198,000.00	$ 395,155.15	$ 790,310.31

74	2	$ 64,767.91	$ 194,303.73	$ 198,000.00	$ 392,303.73	$ 784,607.46
75	2	$ 70,751.66	$ 212,254.99	$ 198,000.00	$ 410,254.99	$ 820,509.97
76	2	$ 72,728.67	$ 218,186.00	$ 198,000.00	$ 416,186.00	$ 832,371.99
77	2	$ 71,139.68	$ 213,419.04	$ 198,000.00	$ 411,419.04	$ 822,838.08
78	2	$ 62,219.77	$ 186,659.31	$ 198,000.00	$ 384,659.31	$ 769,318.63
79	2	$ 89,870.50	$ 269,611.49	$ 198,000.00	$ 467,611.49	$ 935,222.97
80	2	$ 74,680.66	$ 224,041.97	$ 198,000.00	$ 422,041.97	$ 844,083.95
81	2	$ 104,754.60	$ 314,263.81	$ 198,000.00	$ 512,263.81	$ 1,024,527.63
82	2	$ 95,773.64	$ 287,320.91	$ 198,000.00	$ 485,320.91	$ 970,641.83
83	2	$ 91,223.31	$ 273,669.92	$ 198,000.00	$ 471,669.92	$ 943,339.84
84	2	$ 93,049.80	$ 279,149.41	$ 198,000.00	$ 477,149.41	$ 954,298.81
85	2	$ 106,868.96	$ 320,606.87	$ 198,000.00	$ 518,606.87	$ 1,037,213.75
86	2	$ 88,555.26	$ 265,665.77	$ 198,000.00	$ 463,665.77	$ 927,331.55
87	2	$ 117,294.83	$ 351,884.49	$ 198,000.00	$ 549,884.49	$ 1,099,768.99
88	2	$ 103,741.17	$ 311,223.51	$ 198,000.00	$ 509,223.51	$ 1,018,447.02
89	2	$ 98,743.79	$ 296,231.38	$ 198,000.00	$ 494,231.38	$ 988,462.77
90	2	$ 93,389.22	$ 280,167.65	$ 198,000.00	$ 478,167.65	$ 956,335.30
91	2	$ 94,439.14	$ 283,317.41	$ 198,000.00	$ 481,317.41	$ 962,634.82
92	2	$ 107,161.53	$ 321,484.58	$ 198,000.00	$ 519,484.58	$ 1,038,969.16
93	2	$ 77,829.81	$ 233,489.42	$ 198,000.00	$ 431,489.42	$ 862,978.84
94	2	$ 103,747.47	$ 311,242.40	$ 198,000.00	$ 509,242.40	$ 1,018,484.79
95	2	$ 120,507.79	$ 361,523.36	$ 198,000.00	$ 559,523.36	$ 1,119,046.72
96	2	$ 112,889.85	$ 338,669.54	$ 198,000.00	$ 536,669.54	$ 1,073,339.08
97	2	$ 89,608.94	$ 268,826.83	$ 198,000.00	$ 466,826.83	$ 933,653.66
98	2	$ 106,088.45	$ 318,265.35	$ 198,000.00	$ 516,265.35	$ 1,032,530.71
99	2	$ 97,556.00	$ 292,668.01	$ 198,000.00	$ 490,668.01	$ 981,336.03
100	2	$ 94,841.53	$ 284,524.60	$ 198,000.00	$ 482,524.60	$ 965,049.20
101	2	$ 112,021.79	$ 336,065.37	$ 198,000.00	$ 534,065.37	$ 1,068,130.74
102	2	$ 110,524.60	$ 331,573.81	$ 198,000.00	$ 529,573.81	$ 1,059,147.62
103	2	$ 107,175.48	$ 321,526.45	$ 198,000.00	$ 519,526.45	$ 1,039,052.90
104	2	$ 93,742.31	$ 281,226.93	$ 198,000.00	$ 479,226.93	$ 958,453.85
105	2	$ 83,454.82	$ 250,364.45	$ 198,000.00	$ 448,364.45	$ 896,728.89
106	2	$ 105,832.20	$ 317,496.61	$ 198,000.00	$ 515,496.61	$ 1,030,993.22
107	2	$ 106,947.90	$ 320,843.70	$ 198,000.00	$ 518,843.70	$ 1,037,687.40
108	2	$ 100,777.76	$ 302,333.29	$ 198,000.00	$ 500,333.29	$ 1,000,666.57
109	2	$ 98,847.69	$ 296,543.06	$ 198,000.00	$ 494,543.06	$ 989,086.12
110	2	$ 100,389.74	$ 301,169.23	$ 198,000.00	$ 499,169.23	$ 998,338.46
111	2	$ 109,309.65	$ 327,928.96	$ 198,000.00	$ 525,928.96	$ 1,051,857.92
112	2	$ 81,658.93	$ 244,976.79	$ 198,000.00	$ 442,976.79	$ 885,953.57
113	2	$ 96,848.77	$ 290,546.30	$ 198,000.00	$ 488,546.30	$ 977,092.59

114	2	$ 66,776.04	$ 200,328.12	$ 198,000.00	$ 398,328.12	$ 796,656.23
115	2	$ 75,776.95	$ 227,330.85	$ 198,000.00	$ 425,330.85	$ 850,661.70
116	2	$ 80,311.45	$ 240,934.35	$ 198,000.00	$ 438,934.35	$ 877,868.70
117	2	$ 78,479.62	$ 235,438.86	$ 198,000.00	$ 433,438.86	$ 866,877.73
118	2	$ 64,660.47	$ 193,981.40	$ 198,000.00	$ 391,981.40	$ 783,962.79
119	2	$ 82,974.17	$ 248,922.50	$ 198,000.00	$ 446,922.50	$ 893,845.00
120	2	$ 54,419.76	$ 163,259.28	$ 198,000.00	$ 361,259.28	$ 722,518.55
121	2	$ 67,788.25	$ 203,364.76	$ 198,000.00	$ 401,364.76	$ 802,729.52
122	2	$ 72,785.63	$ 218,356.89	$ 198,000.00	$ 416,356.89	$ 832,713.78
123	2	$ 78,140.21	$ 234,420.62	$ 198,000.00	$ 432,420.62	$ 864,841.24
124	2	$ 77,090.29	$ 231,270.86	$ 198,000.00	$ 429,270.86	$ 858,541.72
125	2	$ 64,409.49	$ 193,228.48	$ 198,000.00	$ 391,228.48	$ 782,456.95
126	2	$ 93,720.78	$ 281,162.34	$ 198,000.00	$ 479,162.34	$ 958,324.68
127	2	$ 67,783.18	$ 203,349.54	$ 198,000.00	$ 401,349.54	$ 802,699.07
128	2	$ 51,021.64	$ 153,064.91	$ 198,000.00	$ 351,064.91	$ 702,129.82
129	2	$ 58,644.91	$ 175,934.73	$ 198,000.00	$ 373,934.73	$ 747,869.46
130	3	$ 65,440.97	$ 196,322.92	$ 198,000.00	$ 394,322.92	$ 1,182,968.75
131	3	$ 73,954.14	$ 221,862.43	$ 198,000.00	$ 419,862.43	$ 1,259,587.29
132	3	$ 76,687.89	$ 230,063.67	$ 198,000.00	$ 428,063.67	$ 1,284,191.02
133	3	$ 59,507.63	$ 178,522.90	$ 198,000.00	$ 376,522.90	$ 1,129,568.71
134	3	$ 61,010.15	$ 183,030.46	$ 198,000.00	$ 381,030.46	$ 1,143,091.39
135	3	$ 64,353.94	$ 193,061.82	$ 198,000.00	$ 391,061.82	$ 1,173,185.46
136	3	$ 77,788.33	$ 233,365.00	$ 198,000.00	$ 431,365.00	$ 1,294,095.01
137	3	$ 88,095.77	$ 264,287.31	$ 198,000.00	$ 462,287.31	$ 1,386,861.94
138	3	$ 65,718.38	$ 197,155.15	$ 198,000.00	$ 395,155.15	$ 1,185,465.46
139	3	$ 64,767.91	$ 194,303.73	$ 198,000.00	$ 392,303.73	$ 1,176,911.19
140	3	$ 70,751.66	$ 212,254.99	$ 198,000.00	$ 410,254.99	$ 1,230,764.96
141	3	$ 72,728.67	$ 218,186.00	$ 198,000.00	$ 416,186.00	$ 1,248,557.99
142	3	$ 71,139.68	$ 213,419.04	$ 198,000.00	$ 411,419.04	$ 1,234,257.13
143	3	$ 62,219.77	$ 186,659.31	$ 198,000.00	$ 384,659.31	$ 1,153,977.94
144	3	$ 89,870.50	$ 269,611.49	$ 198,000.00	$ 467,611.49	$ 1,402,834.46
145	3	$ 74,680.66	$ 224,041.97	$ 198,000.00	$ 422,041.97	$ 1,266,125.92
146	3	$ 104,754.60	$ 314,263.81	$ 198,000.00	$ 512,263.81	$ 1,536,791.44
147	3	$ 95,773.64	$ 287,320.91	$ 198,000.00	$ 485,320.91	$ 1,455,962.74
148	3	$ 91,223.31	$ 273,669.92	$ 198,000.00	$ 471,669.92	$ 1,415,009.76
149	3	$ 93,049.80	$ 279,149.41	$ 198,000.00	$ 477,149.41	$ 1,431,448.22
150	3	$ 106,868.96	$ 320,606.87	$ 198,000.00	$ 518,606.87	$ 1,555,820.62
151	3	$ 88,555.26	$ 265,665.77	$ 198,000.00	$ 463,665.77	$ 1,390,997.32
152	3	$ 117,294.83	$ 351,884.49	$ 198,000.00	$ 549,884.49	$ 1,649,653.48
153	3	$ 103,741.17	$ 311,223.51	$ 198,000.00	$ 509,223.51	$ 1,527,670.53

154	3	$ 98,743.79	$ 296,231.38	$ 198,000.00	$ 494,231.38	$ 1,482,694.15
155	3	$ 93,389.22	$ 280,167.65	$ 198,000.00	$ 478,167.65	$ 1,434,502.95
156	3	$ 94,439.14	$ 283,317.41	$ 198,000.00	$ 481,317.41	$ 1,443,952.23
157	3	$ 107,161.53	$ 321,484.58	$ 198,000.00	$ 519,484.58	$ 1,558,453.74
158	3	$ 77,829.81	$ 233,489.42	$ 198,000.00	$ 431,489.42	$ 1,294,468.26
159	3	$ 103,747.47	$ 311,242.40	$ 198,000.00	$ 509,242.40	$ 1,527,727.19
160	3	$ 120,507.79	$ 361,523.36	$ 198,000.00	$ 559,523.36	$ 1,678,570.08
161	3	$ 112,889.85	$ 338,669.54	$ 198,000.00	$ 536,669.54	$ 1,610,008.61
162	3	$ 89,608.94	$ 268,826.83	$ 198,000.00	$ 466,826.83	$ 1,400,480.48
163	3	$ 106,088.45	$ 318,265.35	$ 198,000.00	$ 516,265.35	$ 1,548,796.06
164	3	$ 97,556.00	$ 292,668.01	$ 198,000.00	$ 490,668.01	$ 1,472,004.04
165	3	$ 94,841.53	$ 284,524.60	$ 198,000.00	$ 482,524.60	$ 1,447,573.79
166	3	$ 112,021.79	$ 336,065.37	$ 198,000.00	$ 534,065.37	$ 1,602,196.10
167	3	$ 110,524.60	$ 331,573.81	$ 198,000.00	$ 529,573.81	$ 1,588,721.42
168	3	$ 107,175.48	$ 321,526.45	$ 198,000.00	$ 519,526.45	$ 1,558,579.35
169	3	$ 93,742.31	$ 281,226.93	$ 198,000.00	$ 479,226.93	$ 1,437,680.78
170	3	$ 83,454.82	$ 250,364.45	$ 198,000.00	$ 448,364.45	$ 1,345,093.34
171	3	$ 105,832.20	$ 317,496.61	$ 198,000.00	$ 515,496.61	$ 1,546,489.82
172	3	$ 106,947.90	$ 320,843.70	$ 198,000.00	$ 518,843.70	$ 1,556,531.10
173	3	$ 100,777.76	$ 302,333.29	$ 198,000.00	$ 500,333.29	$ 1,500,999.86
174	3	$ 98,847.69	$ 296,543.06	$ 198,000.00	$ 494,543.06	$ 1,483,629.18
175	3	$ 100,389.74	$ 301,169.23	$ 198,000.00	$ 499,169.23	$ 1,497,507.69
176	3	$ 109,309.65	$ 327,928.96	$ 198,000.00	$ 525,928.96	$ 1,577,786.87
177	3	$ 81,658.93	$ 244,976.79	$ 198,000.00	$ 442,976.79	$ 1,328,930.36
178	3	$ 96,848.77	$ 290,546.30	$ 198,000.00	$ 488,546.30	$ 1,465,638.89
179	3	$ 66,776.04	$ 200,328.12	$ 198,000.00	$ 398,328.12	$ 1,194,984.35
180	3	$ 75,776.95	$ 227,330.85	$ 198,000.00	$ 425,330.85	$ 1,275,992.54
181	3	$ 80,311.45	$ 240,934.35	$ 198,000.00	$ 438,934.35	$ 1,316,803.05
182	3	$ 78,479.62	$ 235,438.86	$ 198,000.00	$ 433,438.86	$ 1,300,316.59
183	3	$ 64,660.47	$ 193,981.40	$ 198,000.00	$ 391,981.40	$ 1,175,944.19
184	3	$ 82,974.17	$ 248,922.50	$ 198,000.00	$ 446,922.50	$ 1,340,767.49
185	3	$ 54,419.76	$ 163,259.28	$ 198,000.00	$ 361,259.28	$ 1,083,777.83
186	3	$ 67,788.25	$ 203,364.76	$ 198,000.00	$ 401,364.76	$ 1,204,094.28
187	3	$ 72,785.63	$ 218,356.89	$ 198,000.00	$ 416,356.89	$ 1,249,070.66
188	3	$ 78,140.21	$ 234,420.62	$ 198,000.00	$ 432,420.62	$ 1,297,261.86
189	3	$ 77,090.29	$ 231,270.86	$ 198,000.00	$ 429,270.86	$ 1,287,812.59
190	3	$ 64,409.49	$ 193,228.48	$ 198,000.00	$ 391,228.48	$ 1,173,685.43
191	3	$ 93,720.78	$ 281,162.34	$ 198,000.00	$ 479,162.34	$ 1,437,487.02
192	3	$ 67,783.18	$ 203,349.54	$ 198,000.00	$ 401,349.54	$ 1,204,048.61
193	3	$ 51,021.64	$ 153,064.91	$ 198,000.00	$ 351,064.91	$ 1,053,194.73

194	3	$ 58,644.91	$ 175,934.73	$ 198,000.00	$ 373,934.73	$ 1,121,804.19
195	4	$ 65,440.97	$ 196,322.92	$ 198,000.00	$ 394,322.92	$ 1,577,291.67
196	4	$ 73,954.14	$ 221,862.43	$ 198,000.00	$ 419,862.43	$ 1,679,449.72
197	4	$ 76,687.89	$ 230,063.67	$ 198,000.00	$ 428,063.67	$ 1,712,254.69
198	4	$ 59,507.63	$ 178,522.90	$ 198,000.00	$ 376,522.90	$ 1,506,091.61
199	4	$ 61,010.15	$ 183,030.46	$ 198,000.00	$ 381,030.46	$ 1,524,121.85
200	4	$ 64,353.94	$ 193,061.82	$ 198,000.00	$ 391,061.82	$ 1,564,247.29
201	4	$ 77,788.33	$ 233,365.00	$ 198,000.00	$ 431,365.00	$ 1,725,460.02
202	4	$ 88,095.77	$ 264,287.31	$ 198,000.00	$ 462,287.31	$ 1,849,149.25
203	4	$ 65,718.38	$ 197,155.15	$ 198,000.00	$ 395,155.15	$ 1,580,620.61
204	4	$ 64,767.91	$ 194,303.73	$ 198,000.00	$ 392,303.73	$ 1,569,214.92
205	4	$ 70,751.66	$ 212,254.99	$ 198,000.00	$ 410,254.99	$ 1,641,019.94
206	4	$ 72,728.67	$ 218,186.00	$ 198,000.00	$ 416,186.00	$ 1,664,743.99
207	4	$ 71,139.68	$ 213,419.04	$ 198,000.00	$ 411,419.04	$ 1,645,676.17
208	4	$ 62,219.77	$ 186,659.31	$ 198,000.00	$ 384,659.31	$ 1,538,637.25
209	4	$ 89,870.50	$ 269,611.49	$ 198,000.00	$ 467,611.49	$ 1,870,445.94
210	4	$ 74,680.66	$ 224,041.97	$ 198,000.00	$ 422,041.97	$ 1,688,167.90
211	4	$ 104,754.60	$ 314,263.81	$ 198,000.00	$ 512,263.81	$ 2,049,055.26
212	4	$ 95,773.64	$ 287,320.91	$ 198,000.00	$ 485,320.91	$ 1,941,283.65
213	4	$ 91,223.31	$ 273,669.92	$ 198,000.00	$ 471,669.92	$ 1,886,679.69
214	4	$ 93,049.80	$ 279,149.41	$ 198,000.00	$ 477,149.41	$ 1,908,597.62
215	4	$ 106,868.96	$ 320,606.87	$ 198,000.00	$ 518,606.87	$ 2,074,427.50
216	4	$ 88,555.26	$ 265,665.77	$ 198,000.00	$ 463,665.77	$ 1,854,663.09
217	4	$ 117,294.83	$ 351,884.49	$ 198,000.00	$ 549,884.49	$ 2,199,537.97
218	4	$ 103,741.17	$ 311,223.51	$ 198,000.00	$ 509,223.51	$ 2,036,894.05
219	4	$ 98,743.79	$ 296,231.38	$ 198,000.00	$ 494,231.38	$ 1,976,925.53
220	4	$ 93,389.22	$ 280,167.65	$ 198,000.00	$ 478,167.65	$ 1,912,670.60
221	4	$ 94,439.14	$ 283,317.41	$ 198,000.00	$ 481,317.41	$ 1,925,269.63
222	4	$ 107,161.53	$ 321,484.58	$ 198,000.00	$ 519,484.58	$ 2,077,938.32
223	4	$ 77,829.81	$ 233,489.42	$ 198,000.00	$ 431,489.42	$ 1,725,957.68
224	4	$ 103,747.47	$ 311,242.40	$ 198,000.00	$ 509,242.40	$ 2,036,969.58
225	4	$ 120,507.79	$ 361,523.36	$ 198,000.00	$ 559,523.36	$ 2,238,093.44
226	4	$ 112,889.85	$ 338,669.54	$ 198,000.00	$ 536,669.54	$ 2,146,678.15
227	4	$ 89,608.94	$ 268,826.83	$ 198,000.00	$ 466,826.83	$ 1,867,307.31
228	4	$ 106,088.45	$ 318,265.35	$ 198,000.00	$ 516,265.35	$ 2,065,061.41
229	4	$ 97,556.00	$ 292,668.01	$ 198,000.00	$ 490,668.01	$ 1,962,672.06
230	4	$ 94,841.53	$ 284,524.60	$ 198,000.00	$ 482,524.60	$ 1,930,098.39
231	4	$ 112,021.79	$ 336,065.37	$ 198,000.00	$ 534,065.37	$ 2,136,261.47
232	4	$ 110,524.60	$ 331,573.81	$ 198,000.00	$ 529,573.81	$ 2,118,295.23
233	4	$ 107,175.48	$ 321,526.45	$ 198,000.00	$ 519,526.45	$ 2,078,105.80

234	4	$ 93,742.31	$ 281,226.93	$ 198,000.00	$ 479,226.93	$ 1,916,907.71
235	4	$ 83,454.82	$ 250,364.45	$ 198,000.00	$ 448,364.45	$ 1,793,457.79
236	4	$ 105,832.20	$ 317,496.61	$ 198,000.00	$ 515,496.61	$ 2,061,986.43
237	4	$ 106,947.90	$ 320,843.70	$ 198,000.00	$ 518,843.70	$ 2,075,374.80
238	4	$ 100,777.76	$ 302,333.29	$ 198,000.00	$ 500,333.29	$ 2,001,333.14
239	4	$ 98,847.69	$ 296,543.06	$ 198,000.00	$ 494,543.06	$ 1,978,172.23
240	4	$ 100,389.74	$ 301,169.23	$ 198,000.00	$ 499,169.23	$ 1,996,676.91
241	4	$ 109,309.65	$ 327,928.96	$ 198,000.00	$ 525,928.96	$ 2,103,715.83
242	4	$ 81,658.93	$ 244,976.79	$ 198,000.00	$ 442,976.79	$ 1,771,907.14
243	4	$ 96,848.77	$ 290,546.30	$ 198,000.00	$ 488,546.30	$ 1,954,185.19
244	4	$ 66,776.04	$ 200,328.12	$ 198,000.00	$ 398,328.12	$ 1,593,312.47
245	4	$ 75,776.95	$ 227,330.85	$ 198,000.00	$ 425,330.85	$ 1,701,323.39
246	4	$ 80,311.45	$ 240,934.35	$ 198,000.00	$ 438,934.35	$ 1,755,737.39
247	4	$ 78,479.62	$ 235,438.86	$ 198,000.00	$ 433,438.86	$ 1,733,755.46
248	4	$ 64,660.47	$ 193,981.40	$ 198,000.00	$ 391,981.40	$ 1,567,925.58
249	4	$ 82,974.17	$ 248,922.50	$ 198,000.00	$ 446,922.50	$ 1,787,689.99
250	4	$ 54,419.76	$ 163,259.28	$ 198,000.00	$ 361,259.28	$ 1,445,037.11
251	4	$ 67,788.25	$ 203,364.76	$ 198,000.00	$ 401,364.76	$ 1,605,459.04
252	4	$ 72,785.63	$ 218,356.89	$ 198,000.00	$ 416,356.89	$ 1,665,427.55
253	4	$ 78,140.21	$ 234,420.62	$ 198,000.00	$ 432,420.62	$ 1,729,682.48
254	4	$ 77,090.29	$ 231,270.86	$ 198,000.00	$ 429,270.86	$ 1,717,083.45
255	4	$ 64,409.49	$ 193,228.48	$ 198,000.00	$ 391,228.48	$ 1,564,913.91
256	4	$ 93,720.78	$ 281,162.34	$ 198,000.00	$ 479,162.34	$ 1,916,649.36
257	4	$ 67,783.18	$ 203,349.54	$ 198,000.00	$ 401,349.54	$ 1,605,398.14
258	4	$ 51,021.64	$ 153,064.91	$ 198,000.00	$ 351,064.91	$ 1,404,259.65
259	4	$ 58,644.91	$ 175,934.73	$ 198,000.00	$ 373,934.73	$ 1,495,738.93

See text for data collection methods and details.

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APPENDIX G. PROBABILITY OF MISSION SUCCESS

	DP#	Success	P hat	Lower CI 95%	Relative Cost
0	79	99	0.99	0.97040	$935,222.97
1	106	77	0.77	0.68710	$1,030,993.22
2	110	89	0.89	0.82836	$998,338.46
3	140	81	0.81	0.73272	$1,230,764.96
4	141	59	0.59	0.49312	$1,248,557.99
5	144	93	0.93	0.87974	$1,402,834.46
6	150	64	0.64	0.54545	$1,555,820.62
7	159	60	0.6	0.50350	$1,527,727.19
8	163	78	0.78	0.69840	$1,548,796.06
9	171	88	0.88	0.81599	$1,546,489.82
10	172	60	0.6	0.50350	$1,556,531.10
11	175	92	0.92	0.86656	$1,497,507.69
12	176	54	0.54	0.44182	$1,577,786.87
13	201	99	0.99	0.97040	$1,725,460.02
14	205	100	1	1.00000	$1,641,019.94
15	206	100	1	1.00000	$1,664,743.99
16	209	100	1	1.00000	$1,870,445.94
17	211	97	0.97	0.93640	$2,049,055.26
18	212	83	0.83	0.75601	$1,941,283.65
19	215	100	1	1.00000	$2,074,427.50
20	221	52	0.52	0.42159	$1,925,269.63
21	224	100	1	1.00000	$2,036,969.58
22	226	71	0.71	0.62061	$2,146,678.15
23	227	88	0.88	0.81599	$1,867,307.31
24	228	100	1	1.00000	$2,065,061.41
25	229	81	0.81	0.73272	$1,962,672.06
26	233	96	0.96	0.92140	$2,078,105.80
27	236	100	1	1.00000	$2,061,986.43
28	237	99	0.99	0.97040	$2,075,374.80
29	240	100	1	1.00000	$1,996,676.91
30	241	100	1	1.00000	$2,103,715.83
31	246	77	0.77	0.68710	$1,755,737.39

See text for data collection methods and details.

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